CONTINUOUS SEISMIC PROFILES ALONG THE PROPOSED WATER INTAKE TUNNEL ROUTE — CITY OF DETROIT LAKE HURON WATER SUPPLY PROJECT

by

William F. MacLean

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Sparker traverses in deeper water were made with the University of Michigan Research Vessel INLAND SEAS with Richard Thibault as captain, and inshore traverses were made aboard a DWS boat with Harry Rahn as boatman.

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ABSTRACT

Four off-shore and three near-shore Continuous Seismic Profiler traverses were taken in southwestern Lake Huron along the route of the proposed water intake tunnel of the City of Detroit Department of Water Supply. One near-shore and two off-shore Seismic Profiler traverses (extending from 800 ft to 28,700 ft off-shore) passed as closely as possible to three test boreholes located 8,000 ft, 16,000 ft and 26,000 ft from shore. These traverses revealed the bottom reflecting horizon, one sub-bottom reflecting horizon which could be identified, and their multiple reflections.

The sub-bottom reflecting horizon was correlated with the top of the Antrim formation, i.e., the top of a shale bed about 106 ft below lake bottom. The records indicated that the top of the Antrim shale has a very low dip (about 5 ft), a mildly undulating topography, and is not incised by buried glacial channels.

Side profiles, parallel to and 1500 ft north and south of the center line, supported these conclusions. The side profiles extended from 290 ft off-shore to a maximum of 29,400 ft off-shore.

Sound velocities determined from reflection times taken from the Continuous Seismic Profiler records and thicknesses from borehole logs gave a sound velocity of 5045 ft/sec in the glacial drift.

Descriptions of the equipment, vessels, operating procedures, principles of interpretation, and method of interpretation are given.

INTRODUCTION

Engineers are well acquainted with the problems of determining the attitude and extent of a geological formation which is vital to the construction of an underground installation — the problem is compounded when the formation lies under a body of water. Although test borings may outline the limits of the beds under investigation, their cost restricts the number, which in turn, leaves gaps in the known dimensions of the bed. When tunneling under a water body is involved, as in the proposed water intake tunnel of the Department of Water Supply, the necessity of determining the attitude of the beds, the thickness of overburden, and the existence of buried channels filled with permeable materials is of the utmost importance.

Geophysical methods have been used on land to provide needed information for underground structures; but it is only recently that such methods have been extensively applied to underwater engineering problems. The advent of the Continuous Seismic Profiler, or, as it is also called, the Sub-bottom Depth Recorder, Continuous Stratification Profiler (or, if a spark sound source is used, a Sparker), has permitted geophysical methods to be used quickly and easily over large areas of submarine geology. The Continuous Seismic Profiler, which originated at the Woods Hole Oceanographic Institution (Knott and Hersey, 1956) was further developed at the Lamont Geological Observatory (Beckmann, _et al_., 1959; Ewing, _et al_., 1960), utilizes some aspects of marine echo-sounding and some of seismic reflection shooting. The echo sounder's principle of

a continuous series of sound pulses and automatic recording of the return echoes on a moving strip chart is combined with the seismic reflection technique of selected ranges of lower sound frequencies to provide greater penetration of the sediments.

A Continuous Seismic Profiler was used to delineate the topographic relief of the Antrim formation along the proposed route of an intake water tunnel in the southwestern end of Lake Huron. Four test borings (spaced 8,000 ft apart) revealed the characteristics of the sediments, as well as the very low dip of the shale bed, but, of course, could not give information as to the existence of buried channels between the boreholes. The profiles taken by the Continuous Seismic Profiler confirmed the essentially flat lying dip of the top of the shale and indicated that only minor undulations of the top of the Antrim formation occur.

EQUIPMENT AND METHODS OF OPERATION

Continuous Seismic Profiler

The essential components of a continuous seismic profile study consist of a device to produce sound, a receiving and recording mechanism, and a vehicle to transport them over the required track. With these components, regulated short sound pulses are generated which travel through the water to be reflected from the bottom and sub-bottom horizons. The reflected sound is detected, amplified, and recorded in order that the travel times of the sound pulses may be measured from the source to the various reflecting horizons and converted to depth readings. Because the Continuous Seismic Profiler (manufactured by Marine Geophysical Services Corp.) used by the University of Michigan in this investigation generates a broad-band sound by means of an underwater spark, the equipment will be referred to as a "Sparker."

The Sparker components are illustrated by the diagram of Figure 1 and the photographs of Figure 3. The series of events which leads to a record of the sub-bottom geology begins with the sound created by a 12,000 volt underwater spark discharge. The sound, which is about as loud as a small blasting cap, occurs when a 12,000 volt spark jumps across the gap of an electrode contained in a plastic bottle filled with a four percent salt solution. The bottle was towed astern of the ship by means of a 245-foot coaxial cable which is kept afloat by plastic net floats.

High voltage current for the spark is produced by a spark

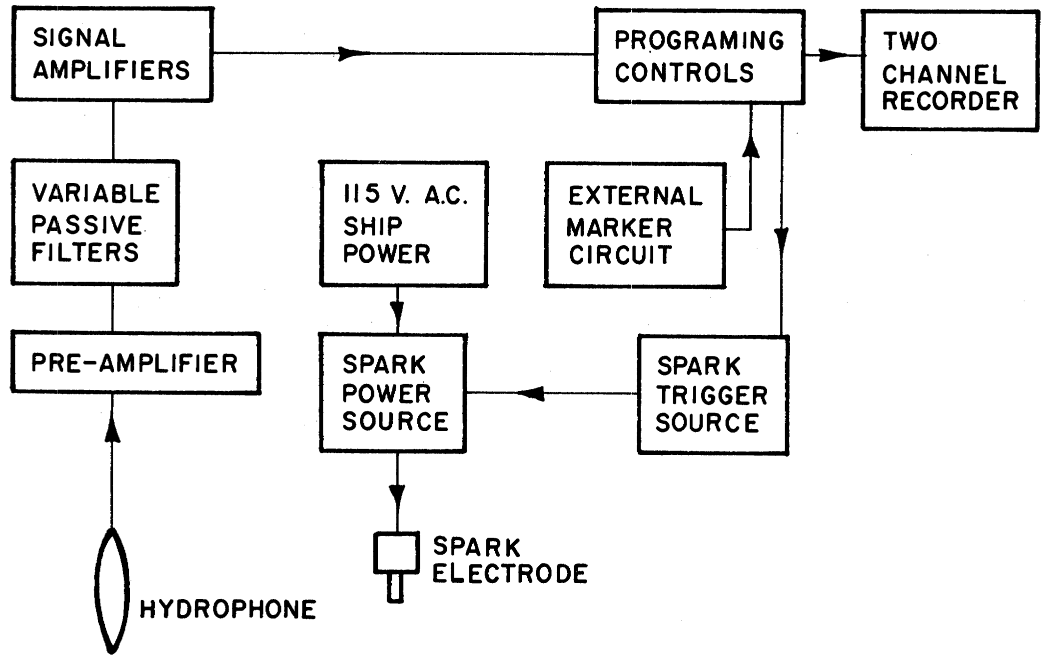


Fig. 1 Schematic diagram of continuous seismic profiler (sparker) equipment.

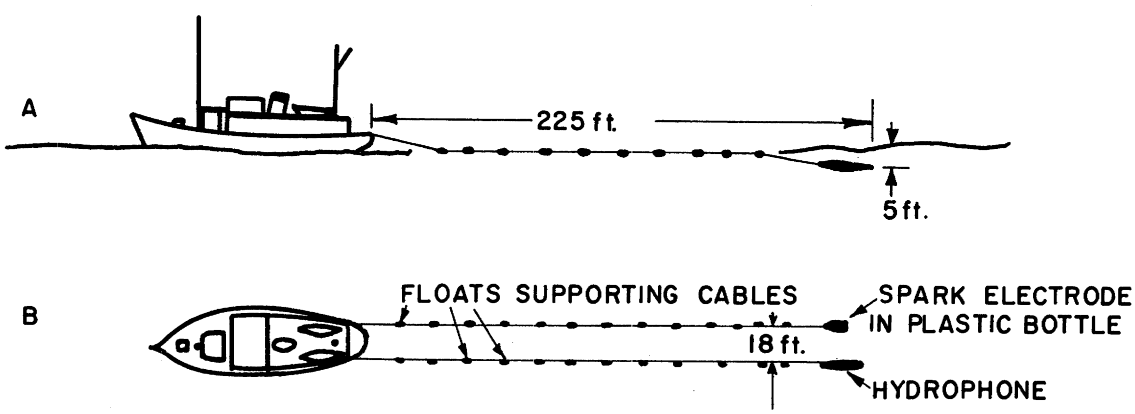


Fig. 2 Diagram of towing arrangement showing relationship of towing vessel, hydrophone, and spark electrode.

power source that uses a transformer, rectifier tube, resistors, and two 1 mfd. 15,000 v. condensers to transform the 115 v. 60 cps A.C. ship power to the necessary high voltage current. The electrical potential stored in the two condensers is discharged when the air in an air gap is ionized by a trigger spark regulated by the programming and recorder controls. The short bursts of sound created by the spark, which may be programmed to occur from once every two seconds to sixteen times a second, travel through the water to the bottom where part of the energy is reflected, and part penetrates the bottom to be reflected from various sub-bottom reflecting horizons.

The reflected sound is detected and converted to an electrical signal by a hydrophone towed parallel with, and about 20 ft from, the spark electrode. The weak signal from the hydrophone is amplified by a fixed gain pre-amplifier and matched in impedance to two Allison filters. After the pre-amplification stage the signal follows two channels; therefore the passive Allison filters may be adjusted to pass different bands of frequencies in each channel. The frequency band selected will be determined by the penetration and resolution desired, the sediments from which the sound is reflected, the signal-to-noise ratio revealed by the record, etc. The use of two channels permits different information to be recorded on each channel.

The selected signals from each filter pass to their respective signal amplifiers. The signal amplifiers not only build up the signals to a level where they will record on the electro-chemical paper in the recorder, but also program the intensity range of the signals and select the type of rectifi-

cation (full-wave or half-wave) which will be used. The strong, rectified signals pass through program and phase switches to double duty commutators driven by the recorder motor. The commutators select that portion of the signal which is to be recorded and also determine the timing of the trigger pulse which initiates the 12,000 v. spark discharge.

The recorder used with the Sparker is an Alden "flying spot" helix recorder driven by gear trains and a two-speed synchronous motor. The helix-type graphic recorder approaches the problem of high resolution with rapid writing speeds by using a moving contact between a straightedge electrode and a wire helix mounted on a rotating drum to record the events occurring during one traverse of the moving contact. The two channel recorder has two helixes mounted on the rotating drum that mark out two channels — each approximately 9 inches wide.

Because the width of the record (sweep length) is constant for each channel, a change in the drum's speed of rotation (sweep speed) will change the rate with which the "flying spot" traverses the record. Thus the time period delineated by each sweep depends upon the sweep speed. The Sparker recorder has four sweep speeds - 1/2 second, 1/4 second, 1/8 second, and 1/16 second; therefore the channel width may represent 500 milliseconds, 250 milliseconds, 125 milliseconds, or 62.5 milliseconds depending upon the sweep speed setting. As the instrument is calibrated for a sound velocity in water of 4800 ft per second, these times would be the equivalent of 1200 ft, 600 ft, 300 ft, and 150 ft (reflection time X sound velocity in feet per second).

The synchronous motor-gear train which drives the helix

drum also drives the recorder commutators through a 12 to 1 reduction gear. This means that the commutators rotate once for each 12 revolutions of the helix drum; as each commutator is divided into 12 sectors, each sweep may be identified with a particular contact. The contact which is to initiate the spark via the trigger spark mechanism and to record the incoming signal on the paper is determined by the program control switch. A phase control switch further selects that contact which will permit the recording of the signal following the initiation of the spark. By adjusting the program control and phase control switches, the operator is able to select the desired echoes and eliminate those which would confuse the record.

The damp electro-chemical paper records the signals in tone shades of sepia — the tone shades are proportional to the signal strengths. A paper transport drive permits the selection of a paper drive speed which will record each pulse-echo sequence side by side without blank spaces appearing between the recorded signals.

Each channel on the recorder paper is divided into five equal parts by scale lines which are printed by stylii on the helix drum. An external marker circuit allows a D.C. signal to print a line across both channels whenever marking lines are desired on the record, e.g. at times of navigational fixes.

Vessels and towing arrangements

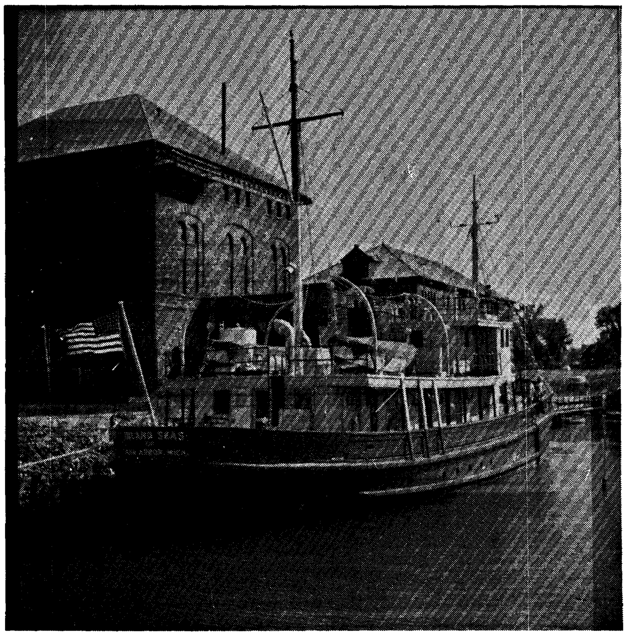
Two vessels were employed in the investigation. Sparker traverses in deeper water were carried out aboard the R/V INLAND SEAS, a 114-foot, twin-screw research vessel of the

University of Michigan. The towing arrangement shown in Figure 2 was used. The Sparker equipment illustrated in Figure 3 and described in previous pages was housed in the after laboratory — the exception being the spark power supply which was placed on the after deck in a specially constructed box equipped with a blower to remove the heat generated by the rectifier tube and resistors.

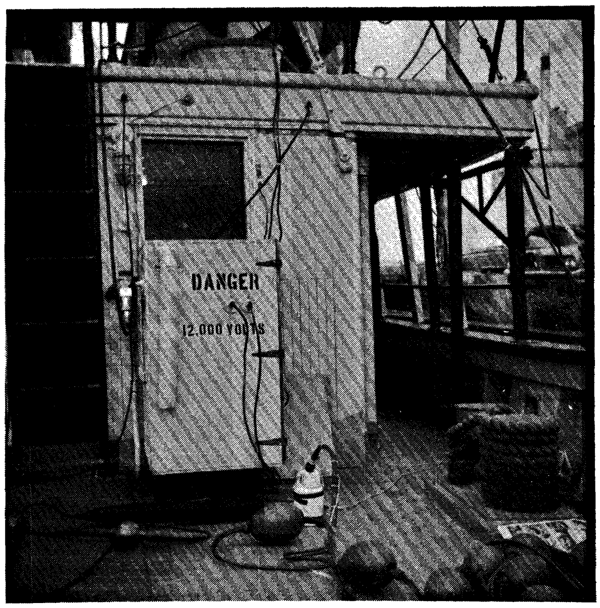
Previous work in Lake Superior indicated that twin-screw operation would result in a poor signal-to-noise ratio which would prevent the detection of faint reflections. Therefore the survey was carried out with only the port engine in operation. An engine speed of approximately 125 rpm resulted in a speed over the ground that varied from 2.9 statute miles per hour to 5.3 mph; the average speed was about 4.0 mph.

Near-shore Sparker traverses were made with the Department of Water Supply boat. The DWS boat is a 28-foot, semi-enclosed, steel craft powered by a 115 hp. gasoline engine. Its draft of 3-1/2 ft permitted the traverses to extend within 300 ft of the shore. The Sparker equipment was transferred from the INLAND SEAS to the DWS boat. Two standard racks containing the pre-amplifier, filters, program controls, and signal amplifiers, together with the recorder, were placed on a bench on the starboard side of the boat. The spark power source was secured behind the boatman's seat on the port side (Fig. 4).

Two 115 v. A.C. 60 cycle portable electric generators used for power were placed in the stern (Fig. 5). A 1000 watt generator provided power for the pre-amplifier, signal amplifiers and recorder. A 2000 watt generator supplied 115 v. A.C.

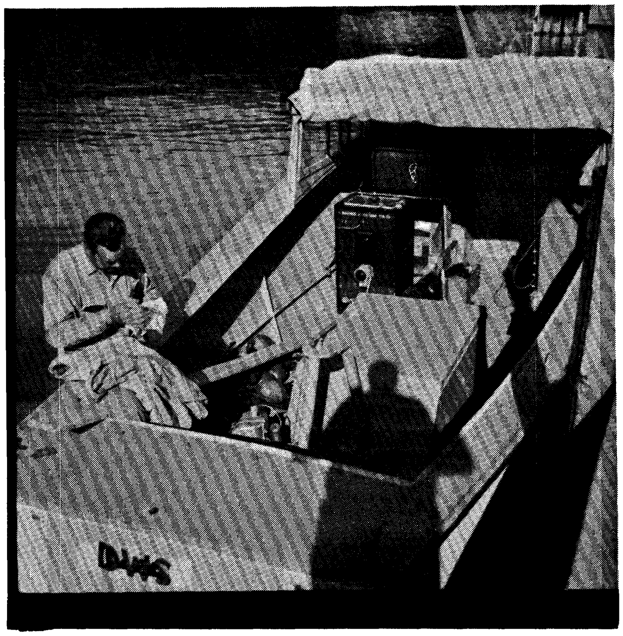


A. The University of Michigan Research Vessel INLAND SEAS.



B. After deck of R/V INLAND SEAS showing spark power source box, hydrophone, plastic bottle containing spark electrode and salt solution, and cables with support floats.

Fig. 3. Continuous Seismic Profiling Equipment (Sparker) used on the R/V INLAND SEAS in the south end of Lake Huron.



A. Department of Water Supply boat with Sparker equipment installed (spark power source-left, recording equipment-right, generators-stern).

B. Sparker recording equipment-left to right: pre-amplifier and passive filters, programming controls and signal amplifiers, and recorder.

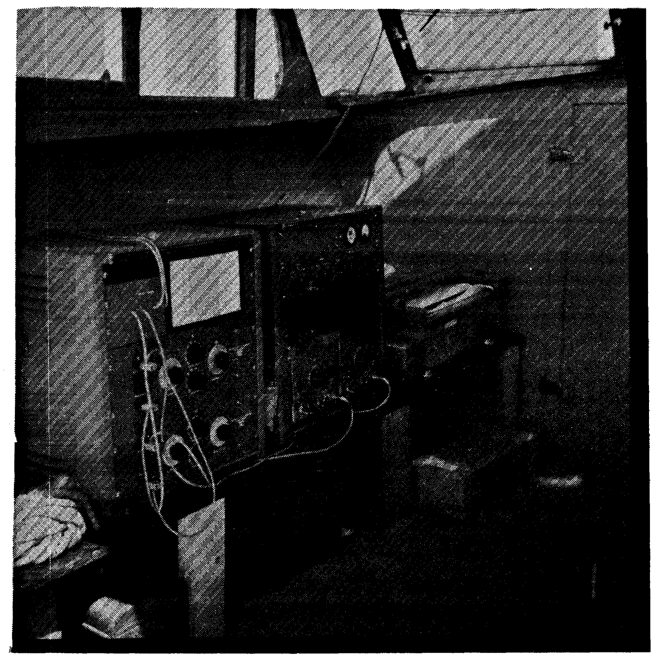


Fig. 4. Continuous Seismic Profiling Equipment (Sparker) used on the Detroit Department of Water Supply boat in the south end of Lake Huron.

Fig. 5. Towing arrangement on the Detroit Department of Water Supply boat. Two portable 115 V.A.C. generators supplied electrical power — 1000 watt 60 cps generator (left) powered instruments; 2000 watt 60 cps generator (right) powered spark power source. The spark electrode cable was secured to the starboard cleat, whereas the hydrophone cable was secured to the outboard end of a 1 x 6 board 12 feet long, resulting in an electrode-hydrophone separation of 12 feet.

power to the spark power source. It was felt that the use of separate generators would permit easier placement than one large generator; in addition, two separate generators would prevent any surging of electric power to the recording instruments as the high voltage charge built up and was discharged by the spark power source.

The spark electrode cables were lashed to a cleat on the port side and the hydrophone cable was tied to the end of a 12-foot x 1 inch x 6 inch board that was lashed athwartships just aft of the engine housing. This arrangement resulted in a separation of 10-12 ft between spark electrode and hydrophone. The lengths of cable overboard were 225 ft, as on the INLAND SEAS. The spark electrode and hydrophone were about five feet beneath the surface.

The speed of the DWS boat on the near-shore traverses varied from 2.3 mph to 3.6 mph; the average speed was about 3.2 mph.

Purpose of the study

The investigation was to determine the topographic relief of the Antrim formation beneath the glacial drift by taking four Sparker profiles. Two center profiles were to be taken along the center line of the proposed water intake tunnel; they were to begin as close to shore as possible and were to pass as closely as possible to the sites of three test boreholes which were located about 8,000 ft, 16,000 ft and 26,000 ft from the shore. Two additional profiles were to be taken, one on each side of the center line. The side profiles would be parallel to, and approximately 1500 ft from the center line of the intake tunnel

(Plate 1). Additional profiles would be taken if anomalous conditions were encountered.

Navigational procedure

Navigational control was carried out by a Department of Water Supply shore party composed of two transit crews and the boatman aboard the DWS boat. Communication between the transit crews and the R/V INLAND SEAS was by walkie-talkie radio. The transceiver aboard the DWS boat, being more powerful than the walkie-talkie sets, was used as a relay station for messages between the transit crews and between the transit crews and the INLAND SEAS when distances became too great for clear walkie-talkie reception.

A transit was established on a platform at the water's edge at station Metcalf and a second instrument was set up at station Sub Hillock about 26,000 ft and approximately NNW from station Metcalf. The transitman at station Metcalf (and later at stations 1500 ft North and 1500 ft South) had two duties to perform. First, he watched the INLAND SEAS through the transit telescope (the instrument was set for the aximuth from Metcalf to the site of the proposed intake) as the ship moved along the course of the Sparker profiler; when the INLAND SEAS crossed the telescope crosshairs and moved away from the proper azimuth, he conned the ship back on the proper course via the walkie-talkie radio. Second, every two minutes during the center profile traverses (and every five minutes during the side profile traverses) the transitman took an azimuth reading on the after mast of the INLAND SEAS. The count-down for the azimuth readings was given by walkie-talkie from the bridge of the INLAND SEAS on

the deeper water traverses and from station Metcalf on the near-shore traverses.

The transit crew at station Sub Hillock took azimuth readings on the after mast of the INLAND SEAS on the time signal sent out over the walkie-talkie radio. Azimuth readings from the second transit were taken from station 19 during the near-shore traverses of July 27. Station 19 is about 10,350 ft SSE of station Metcalf.

During the time that the transit was being taken down from station Metcalf and being re-established at stations 1500 ft North and 1500 ft South for the side Sparker profiles, the INLAND SEAS steered its course with shipboard radar - only azimuth readings from Sub Hillock were obtained at this time. Owing to poor radio reception or atmospheric conditions a few azimuth readings were not taken on the time signal. These omissions resulted in only one transit angle being taken at a particular time; such ship positions on Plate 1 are marked TA (Transit Angle).

A plot of the transit angles for the times indicated gives the ship's positions shown on the chart of the Continuous Seismic Profiling Traverses (Plate 1).

Shipboard procedure

Navigation of the INLAND SEAS and the DWS boat on the Sparker traverses was controlled by the transit crew on shore; the helmsman in each case steered the ship in response to directions from the shore party. Of course, the ship's officers took over navigational control when not on a Sparker traverse and during the time that the transit station was being moved. Ship-

board radar and visual sightings were used at this time. The INLAND SEAS port engine was kept as closely as possible to 125 rpm and towing arrangements were made as described under "Vessels and towing arrangements."

During the deeper water traverses made on July 24, 1962, time count-downs were made over the walkie-talkie radio from the INLAND SEAS. A man stationed at the recording fathometer simultaneously pressed the fathometer marker button and the Sparker external marker circuit button at the command "mark." He then wrote the time on the fathogram and gave the time and depth over the intercom to the Sparker operator; thus at each time check the transit crews on shore took transit angles; a mark and time were recorded on the fathogram; a mark, time and depth were recorded on the Sparker record; and an entry was made in the ship's log.

Sparker programming controls were adjusted before the first traverse was made, and were re-adjusted as conditions dictated. On the North side-traverse, the plastic bottle containing the spark electrode and salt solution ripped open, apparently due to the accumulation of gas brought about by the electrolysis of the salt solution by the spark. The bottle was replaced during the time 1812-1827 of July 24.

Near-shore traverses made on July 27, 1962 with the DWS boat were conducted with the towing arrangement and procedures described on previous pages.

INTERPRETATION OF CONTINUOUS SEISMIC PROFILER RECORDS

The principle underlying continuous seismic profiling is that of a continuous graphic presentation of discrete time measurements — the time measurements begin with the creation of a sound pulse and end with the recording of its echoes. Any factor that influences the character of the initial pulse, its travel time and path through the propagating media, its reflection and (or) absorption by various surfaces, or its final recording will also affect the interpretation of the Profiler record.

The Seismic Profiler initiates a sound pulse when the moving contact of the recorder helix and loop electrode starts its sweep across the recorder paper; the recorder will record any sound which has enough intensity to activate the hydrophone for as long a time as it takes the record brush to wipe across the commutator sector selected by the programming controls. During this period the recorder may respond to the following sounds: the initial sound pulse with its train of reverberations transmitted directly through the water, engine and propeller noise, other ship noise, water and towing noise, echoes from bottom elevations to the front, rear and sides of the sound detector, bottom and bottom multiple echoes, sub-bottom and sub-bottom multiple echoes beneath the sound detector, sub-bottom and sub-bottom multiple echoes from dipping horizons, and spurious signals generated by the equipment. The problem lies in identifying and measuring those record traces that represent real parameters of the sub-bottom geology rather than the many misleading traces which are also a part of the record.

An examination of the Sparker records reproduced in Plates 2-7 will point out the majority of features associated with Continuous Seismic Profiler records. Because these records were taken in an area of smoothly sloping bottom and essentially flat-lying sediments, the characteristic features of rugged bottom topography and dipping sub-bottom horizons are not presented.

Possibly the most easily recognized features of the record are the regularly spaced heavy vertical and light horizontal straight lines. The heavy vertical lines represent navigational marker lines; each line was printed when an external marker circuit button was pressed on the ship's bridge. A second external marker button on the program control panel allows the Sparker operator also to print identification marks on the record. The vertical lines properly identified with the time provide a means of horizontal position control when correlated with navigational fixes determined for the indicated times. The vertical time lines when used in conjunction with the ship's speed form a horizontal distance scale which, being proportional to the ship's speed, varies as the speed changes. The time recorded with the vertical marker line is elapsed clock time recorded in hours and minutes.

Another type of time is indicated by the light, straight, horizontal lines; time in this case is sweep time measured in milliseconds. Sweep time is the time that it takes the moving contact of the helix wire and loop electrode to make one scan across the record. Therefore, it is the time interval during which there takes place the recording of the echoes from the sound pulse that was initiated when the contact began its sweep.

For example, a sweep speed of 1/4 second results in a record channel width equivalent to 250 milliseconds of total travel time or 125 milliseconds of reflection time — each division marked off by the light horizontal lines (scale lines) represents 50 milliseconds of total travel time or 25 milliseconds of reflection time. At the standard calibration sound velocity of 4800 ft per second and 1/4 second sweep speed, the record channel width would be the equivalent of a depth of 600 ft.

The over-all grainy appearance of the record is due to noise (sounds other than the desired signal), chiefly engine, propeller and towing noise. Instrumental noise, electrical and mechanical, is indicated by a regular sequence of light and dark lines or bands which extend completely across the record, usually diagonally from left to right, or horizontally in step-like jumps.

The traces of the sound pulse and its reflections are best seen by viewing the Sparker records obliquely — from approximately the middle of the channel at the left hand edge toward the upper right corner. Each sound trace is composed of a series of heavy black and white lines — the first line of the series denotes the first arrival time. The top of each recording channel is outlined by a sequence of heavy straight black and white lines marked "surface" on the plates. The series represents the outgoing sound pulse and the first line in the series denotes zero sweep time. The next sequence of lines to be seen is the "direct arrival," an undulating band which is particularly wavy at locations marked "change course." The "direct arrival" indicates the time that the sound pulse takes

to travel directly through the water from the sound source to the hydrophone. The change in the distance between sound source and hydrophone that results when the helmsman changes the heading of the ship causes the sound travel time to vary, resulting in undulating "direct arrival" lines.

Bottom and sub-bottom reflections, as well as their multiples, are identified on the record by their dark, apparently continuous, traces which are formed by the regular sequence of echo marks. The darker reflection traces contrast with the lighter marks of the weaker random noise, thereby permitting the visual correlation of the reflection signals.

The factors that influence the recording of bottom and sub-bottom reflections will be discussed in the following paragraphs.

Initial pulse-filtering

Since the initial pulse begins the train of events that leads to the recording of the echo, its length, build-up, shape and timing are important in the final interpretation of the reflected signal. Timing is important in that measurements are made on the assumption that the outgoing pulse occurs at the beginning of the recorder sweep. If the keying is off, time measurements will be in error. Pulse length determines the ability to differentiate between reflecting horizon — short pulses give high resolution, whereas longer pulses cover up detail.

Maries and Beckmann (1961) bring out the fact that the initial pulse builds up quickly; but the first wave of the reflected signal may not be strong enough to print on the

recorder. The delay between the arrival of the first wave and one strong enough to print may be the equivalent of as much as three feet in solid rock.

The initial sound pulse in the Sparker system is created when the spark jumps the gap in the spark electrode which is towed 3-5 ft below the water surface. The spark creates a bubble pulse in the water which also generates sound energy a little later than the original pulse. Because both spark source and sound detector are towed about five feet below the surface, the sound of both pulses follows several paths from the source to the reflector and back to the sound detector. The first arrival (the arrival that is used to compute travel time) goes directly from the source to the reflecting horizon and from the reflecting horizon to the hydrophone. However, waves from the same pulses travel from: (a) source to surface to reflecting horizon to hydrophone, (b) source to surface to reflecting horizon to surface to hydrophone, and (c) source to reflecting horizon to surface to hydrophone.

This series of sound reflections results in a band of dark and light lines below the first arrival line on the record which resembles sedimentary layers. The width of the band of reverberations corresponds to a depth interval of 10-12 ft. It is evident that signals from reflecting horizons which are 10-12 ft below the first horizon would be masked by the train of events following the first arrival of the first horizon. This factor limits the ability of the Sparker to distinguish interfaces which are less than 10-12 ft apart.

The ability of the variable passive filters to select a

particular band of sound frequencies from the broad-band sound pulse permits the resolution and penetration of the sound waves to be controlled. Sound waves in water vary in length from about 86 ft for a frequency of 55 cycles per second to about 14 inches for a frequency of 4186 cycles per second. According to Maries and Beckmann (1961) the resolution which may be attained is theoretically about one-tenth of the wave length; therefore, the maximum error in measuring water depths which may be caused by sound frequencies would be about 9 ft at 55 cps and 1-1/2 inches at 4186 cps. From this it is apparent that higher sound frequencies give better resolution; however, the advantages of higher resolution are tempered by the fact that attenuation of sound in sediments and bedrock increases with frequency. Therefore, lower frequencies must be used to gain penetration despite the poorer resolution. The variable controls of the filters permit a compromise between resolution and penetration to be reached according to the requirements of a particular survey.

Travel time - travel path

Depths to reflecting horizons are calculated by multiplying the velocity of sound in the propagating media by the time interval required for a sound pulse to travel from the sound source to the reflecting horizon, then to the sound detector; hence any factor which serves to change the length of the sound path, or to change the sound velocity along that path, will affect the proper determination of depth. Although depths to reflecting horizons are usually computed from reflection times

measured directly from the record, the reflection time approaches being a measure of vertical distance only in deeper water.

If the same sound transducer were used to send and receive sound pulses (as in a fathometer), the sound path would be perpendicular to a level sea surface; however, a Sparker survey ship tows the spark electrode and hydrophone about five feet under the water surface and from ten to twenty feet apart. As may be seen in Figure 6, the reflection path is not the vertical distance from the surface to the reflecting horizon; but it approaches the vertical distance as depth increases.

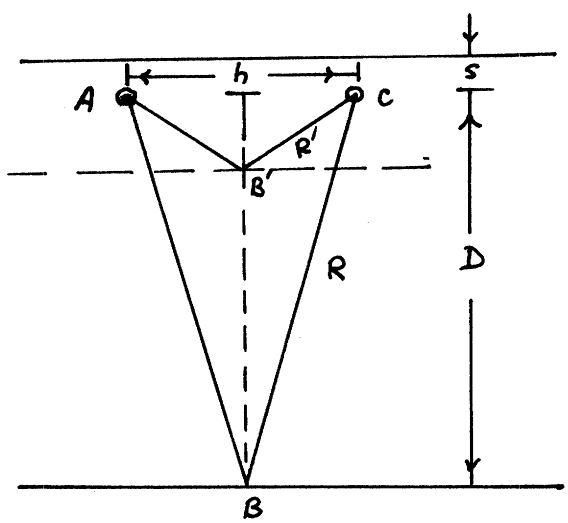


Fig. 6. Sound travel path.

A = sound source

C = sound detector

B, B^1 = reflecting horizons

h = sound source-detector separation

s = distance of sound source-detector below water surface

R, R^1 = distances computed by reflection times + sound velocity in media

D = depth

D + s = actual depth

R + s = measured depth

$R = \sqrt{(D)^2 + (\frac{h}{2})^2}$

$D = \sqrt{(R)^2 - (\frac{h}{2})^2}$

For example, if a spark electrode and hydrophone were towed five feet below the surface and 20 ft apart, a water

depth of 105 ft would be calculated from the Sparker record as being 105.5 ft, which would give an error of 0.48 percent; a water depth of 10 ft would be measured as 16.18 ft, giving an error of 61.8 percent; and a water depth of 6 ft would be measured as 15.05 ft which gives an error of 150.9 percent. Depths to shallow reflecting horizons should be computed with the formula in Figure 6.

Multiple reflections are found in many Profiler records; they represent a lengthening of the sound path which is caused by the re-echoing of sound pulses from the water surface, from the water bottom, from sub-bottom horizons, or from combinations of these elements. An example of a simple multiple reflection would be the trace resulting from the echo of a sub-bottom reflecting horizon which was reflected from the water surface back to the water bottom, then upward again to the hydrophone where it would be detected and recorded as a second sub-bottom reflection. Another example of a multiple reflection would occur if the echo from a sub-bottom horizon traveled upward to the water surface, was reflected downward to the sub-bottom horizon, and upward again to the hydrophone where it would be detected and recorded on the Profiler record.

Multiple reflections are differentiated from actual sub-bottom reflections by accurate measurement of the travel time relationships of the initial reflection and the suspected multiple reflection. Probably the best way to distinguish multiple reflections is by their characteristic of doubling the relief of the initial pulse by the first multiple,

and the doubling by each subsequent multiple of the relief of the multiple above it.

If the trace of the reflecting horizon can be carried to an unconformity, to an area of outcrop, or to the location of a borehole where measurements have been made to probable reflecting horizons, then a positive check can be made as to whether the reflection is of a sub-bottom horizon or is a multiple.

<u>Propagating media</u>

Depths cannot be calculated until the velocity of sound has been determined for the media through which the sound passes. When velocity is known, the product of the velocity and the corrected reflection time (see Fig. 6) will be the depth to the reflecting horizon.

The velocity of sound in a fluid is primarily a function of two factors: density and compressibility. The velocity of sound in water, both of the water body where the survey is conducted and in the pore spaces of the sediments, is of primary concern to Continuous Seismic Profiler operation. The density of water (its mass in grams per cubic centimeter) is a function of temperature, salinity, and pressure. The compressibility of water is the relative change in volume for a given change in pressure; its effect is the packing of more molecules in a given space.

If temperature is increased, density and compressibility decrease, and an increase in the speed of sound takes place. If pressure or salinity is increased, density is increased slightly and compressibility is decreased in greater proportion,

resulting in an increase of sound velocity. Hence, an increase in temperature, salinity, or pressure increases the velocity of sound in water. Sound velocities in water may be determined from hydrographic references, such as the "Hydrographic Manual, Publication 20-2" of the U.S. Coast and Geodetic Survey.

The problem of analyzing the propagation of sound in solids presents a difficult problem, the solution of which depends in large part upon the elastic theory of solids. However, several investigators such as Hamilton (1959; Hamilton et al., 1956), Nafe and Drake (1957), Shumway (1960), and Sutton (Sutton et al., 1957) have correlated a number of properties of unconsolidated and consolidated sediments with sound velocities; the results of these studies permit the determination of sound velocity by an analysis of the properties.

Shumway (1960) states that porosity is the most important single factor causing variation in compressional sound speed. He also (1960, p. 660) lists the following factors and their effect on sound speed:

Factor	Percent Change in Sound Speed
Porosity	16
(Rigidity)	(10-20)
Pressure	11
Temperature	7
Grain aggregate compressibility	3

Sound velocities are also determined by seismic refraction profiling, wide angle reflection profiling, in situ testing by divers, and from borehole logs.

In addition to variations in sound velocity, sediment and rock properties also determine acoustic characteristics such as acoustic impedance (density X velocity), reflection

loss, sound absorption, etc. Differences in properties as revealed by these characteristics determine the strength of the reflected sound signal, i.e., the greater the difference in acoustic impedances of two sediments, the greater the chance for strong reflection from the interface between the sediments.

The Continuous Seismic Profiler is calibrated for a sound velocity of 4800 ft/sec. If sound velocities are not determined for the water, sediments, and bedrock in the area being surveyed, errors in depth determination ranging from fractions of a percent to several hundred percent may be made.

SPARKER SURVEY RESULTS IN SOUTHWESTERN LAKE HURON

Previous paragraphs have pointed out that the quality of Seismic Profiler sub-bottom recording is determined in large part by the nature of the bottom and sub-bottom materials, the depth of water if shallow water depths are involved, the choice of sound frequencies and recording programs, and the signal-to-noise ratio. The quality of Sparker records from the southwestern end of Lake Huron was restricted as a result of several of these factors.

The depth of penetration by the Sparker sound pulses was limited by the presence of sand, gravel, and sandy clay which compose the bottom material of the survey area. The high reflectivity of these materials, together with the sound scattering quality of the boulders, cobbles, and gravel in the glacial drift, restricted the depth of penetration. The large acoustic impedance difference which exists between the glacial till and the late Devonian-Mississippian Antrim shale assures that a high degree of reflectivity will occur at this interface, and that the chance of signals penetrating below this interface are relatively slight.

Shallow water over a good deal of the survey area also hampered the taking of clear records. The short distance between spark source — hydrophone and bottom combined with the high reflectivity of the main interfaces (water-glacial drift and glacial drift-shale) produced conditions favorable to the formation of multiple reflections. The slope of the lake bottom of about one foot in 578 ft (a slope of about 6 ft) and the very low dip of the top of the Antrim shale

(a dip of about 5.2 ft) made distinguishing multiple reflections from sub-bottom reflections very difficult.

The choice of sound frequencies, and therefore the resolution and penetration of the beds, was dictated chiefly by the signal-to-noise ratio. The lower frequencies which would give good penetration could not be used because the ship noise was principally in the sound frequencies below 400 cycles per second. When lower sound frequencies were used, the ship noise masked the sub-bottom echoes. The use of high frequencies which would give good resolution was not emphasized because the purpose of the survey was to determine the topography of the Antrim shale about 106 ft below the water bottom — for this reason the greatest possible penetration was needed. The sound frequencies which were employed represented a compromise between resolution and penetration and were empirically determined.

Interpretation procedure

The procedure listed below was used to arrive at the interpretation of the Sparker records:

1. Plot ship's positions from transit angles.
2. Determine spark electrode-hydrophone locations at the times of the ship navigational fixes.
3. Determine spark electrode-hydrophone positions which were the nearest to the borehole sites.
4. Scale off water depths on fathograms corresponding to spark electrode-hydrophone positions and record on Sparker records.
5. Photograph (using a Watten 25 [deep red] filter) Sparker records near borehole sites. Enlarge $1\frac{1}{2}$ X to: (a) intensify the reflection traces and reduce background, (b) reduce the scaling error when measuring from zero sweep to first arrivals.

6. Scale off first arrivals of reflections on Sparker records.

7. Compare depths of first arrivals (using an initial sound velocity of 4800 ft/sec) with borehole logs.

8. Trace bottom and sub-bottom reflections and multiples to establish continuity of traces.

9. Decide on interpretation of traces, i.e., that the traces represent the bottom reflection and its multiples and the glacial drift-shale interface reflection and its multiples.

10. Compare bottom and sub-bottom traces with borehole logs and compute sound velocity in glacial drift.

11. Decide that no buried channels are shown by Sparker records along traverses, and that the Antrim formation has a very low dip with only relatively minor undulations of its upper surface.

The relationship of the R/V INLAND SEAS fathometer transducer, the aiming point on the ship for the transit sights, and the position of the sound source-detector astern of the ship provided a minor complication when plotting sound source-detector locations and in measuring water depths to be used with navigational fix lines on the Sparker records; therefore, this relationship will be briefly discussed.

The fathometer transducer on the INLAND SEAS is located near the ship's keel about 64 ft forward of the point where the spark electrode-hydrophone cables go over the side; hence, the spark electrode-hydrophone is about 290 ft astern of the transducer. Thus water depths recorded at a given time on the fathometer will be measured beneath the ship, and water depths at the hydrophone must be scaled from the fathogram 290 ft behind the fathogram marker line. This procedure was followed, and water depths determined from the fathogram were recorded at the appropriate points on the Sparker record in

order to circumvent the need for making the corrections to depth readings necessitated by the spark electrode-hydrophone separation.

Transit sights were taken on the after mast of the R/V INLAND SEAS; the after mast is about 240 ft ahead of the spark electrode and hydrophone. Depending upon the speed of the ship, the hydrophone reached the position occupied by the ship at a given time some fraction of a minute later — about 0.7 minute later for the R/V INLAND SEAS, and about 0.8 minute later for the DWS boat. This fact was taken into account when plotting test borehole positions on the records of Sparker traverses.

Since Sparker records are recorded in tone shades of sepia, it was felt that photographing the records through a red filter might lighten the over-all color of the records, and, because the random background noise is less intense than the sound traces, the sound traces might be accentuated. This objective has apparently been achieved, and the photographs made of the records have made easier the task of scaling off first arrivals with a rule graduated in hundredths of an inch.

Velocity determinations

The logs of Test Borehole Nos. 2 and 3 indicate that a boulder and clay layer lies on the shale of the Antrim formation; this layer is not present above the shale in Borehole No. 4. If boulders are present in sufficiently large numbers, the boulder-clay layer would be the sub-bottom reflecting layer. Since the layer is not found in Borehole No. 4, the sub-bottom reflecting horizon at this location would be the shale.

Table 1 is a compilation of measurements made at Sparker locations opposite test boreholes — photographs of Sparker records opposite Test Borehole Nos. 2, 3 and 4 are reproduced as Plates 5-7. As it would be expected that depths to the sub-bottom reflecting horizon would be to the boulder-clay layer in Borehole Nos. 2 and 3 and to the top of the shale in Borehole No. 4, sound velocities in the glacial drift would be:

Borehole		Sound Velocity (ft/sec)
No. 2		5030
		5070
No. 3		5100
		5030
No. 4		5050
		4980
	Average	5043.3

The sound velocity in glacial drift for this locality in Lake Huron has been taken as 5055 ft/sec.

TABLE I

SOUND VELOCITY DETERMINATIONS IN GLACIAL DRIFT (TILL) — SOUTH END OF LAKE HURON

	Test Borehole No. 2						Test Borehole No. 3						Test Borehole No. 4					
	July 27 Metcalf Traverse			Second Metcalf Traverse			First Metcalf Traverse			Second Metcalf Traverse			First Metcalf Traverse			Second Metcalf Traverse		
	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)	Depth (ft)	Time (milli-seconds)	Velocity (ft/sec)
Sub-bottom reflecting horizon at (boulder bed)	93	18.5	5030	93	18.3	5070	104	20.4	5100	104	20.7	5030	---			---		
Sub-bottom reflecting horizon at (top of shale)	101	18.5	5450	101	18.3	5500	110	20.4	5400	110	20.7	5320	104	20.6	5050	104	20.9	4980

CONCLUSIONS

1. Bedrock channels were not found along the Sparker traverses from within 290 ft of shore to a distance of 29,400 ft off-shore.

2. The top of the Antrim formation shows a very slight dip lakewards and only relatively minor undulations of the upper surface.

3. Two reflecting horizons, the water bottom and the top of the Antrim formation, could be identified with any degree of certainty. The remaining echo traces were, for the most part, multiples of the water bottom and the top of the shale.

4. Depths to the top of the shale when computed from Sparker records (using a sound velocity of 5055 ft/sec for glacial drift and reflection times measured from the first arrival of the water bottom to the first arrival of the sub-bottom reflecting horizon) agree within a few feet with depth intervals from water bottom to the top of the shale as scaled from the borehole logs.

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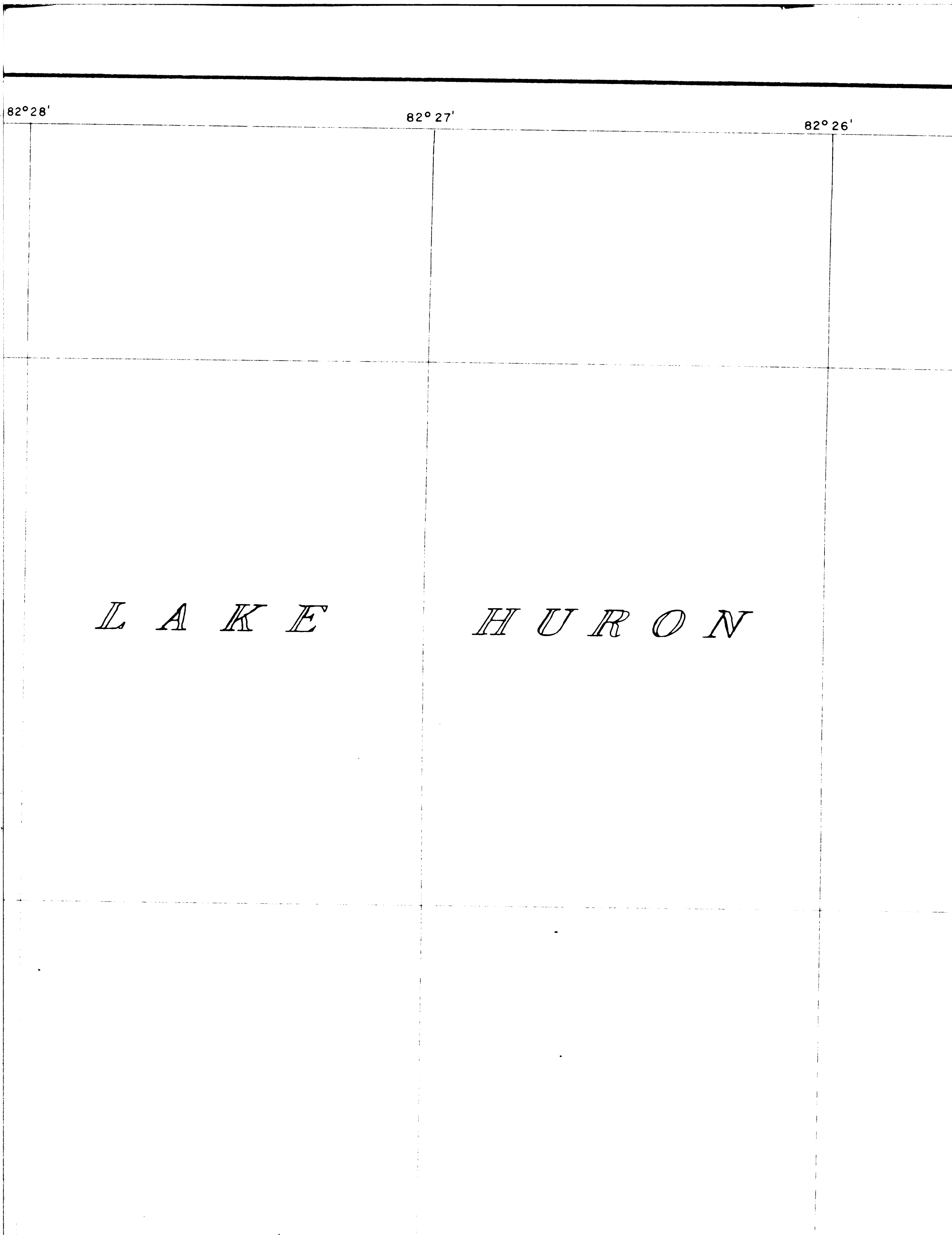
30'
82°29'
82°28'
SUB HILLOCK
25
larris
Rd.


82° 28'
82° 27'
82° 26'
LAKE HURON

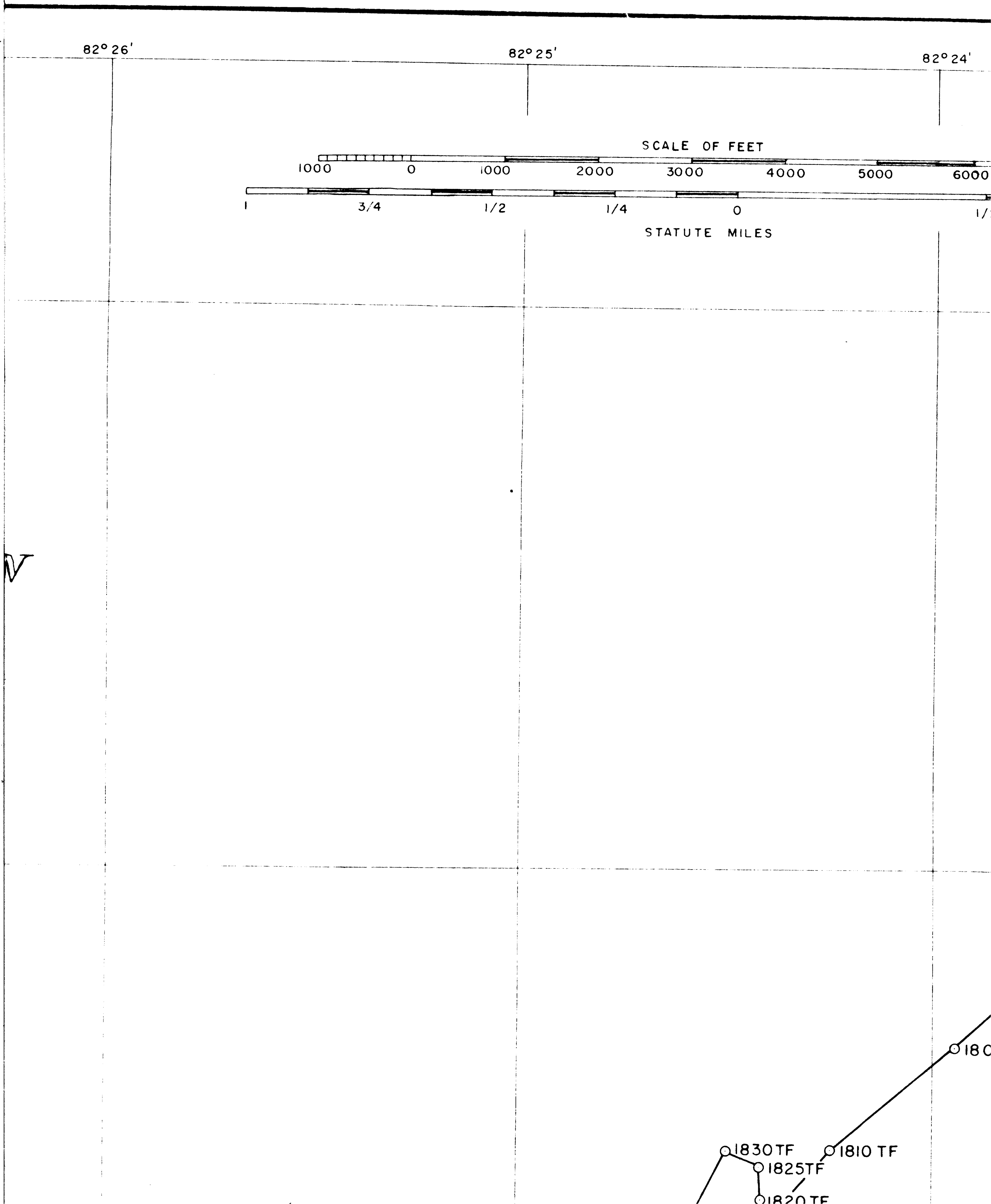
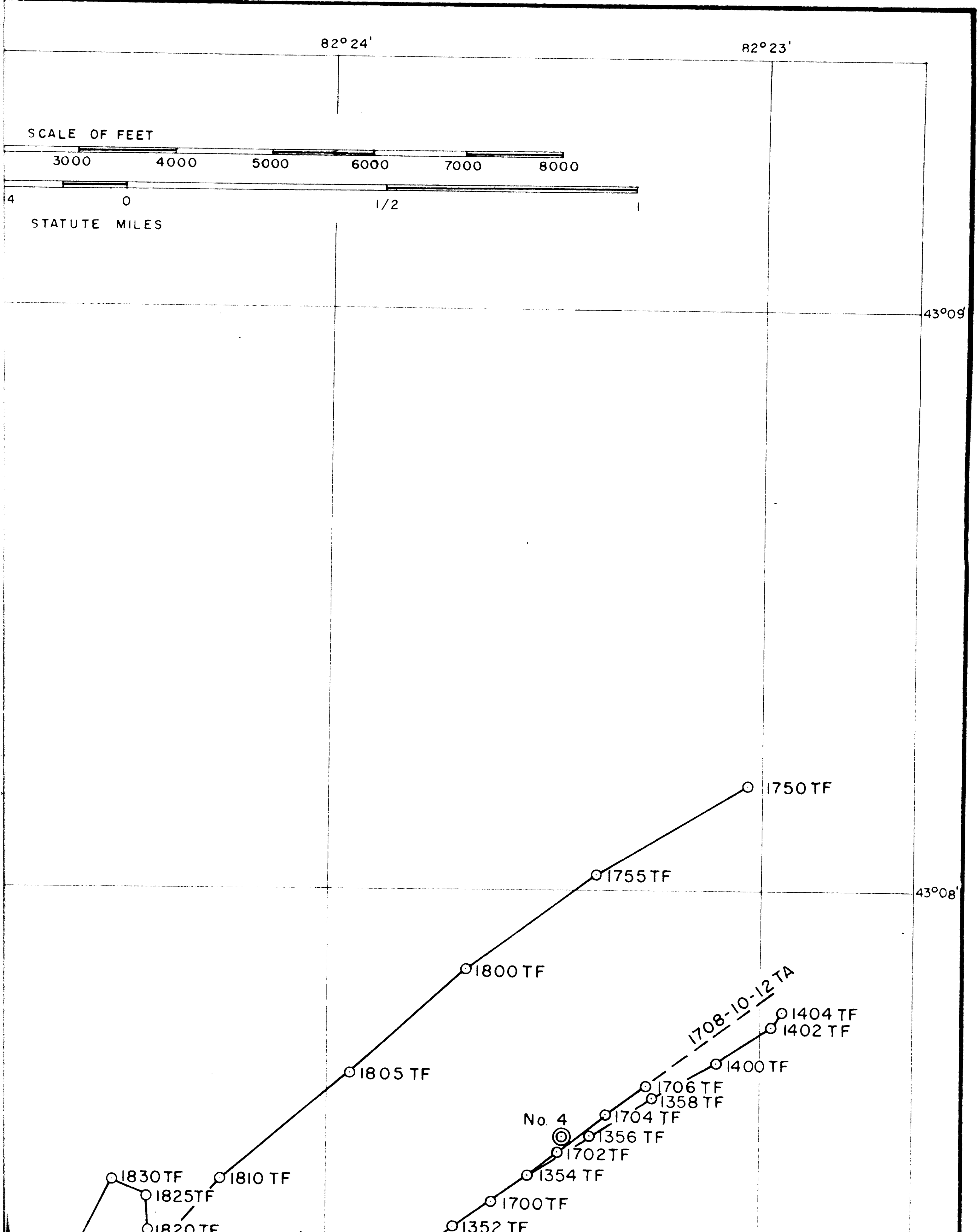
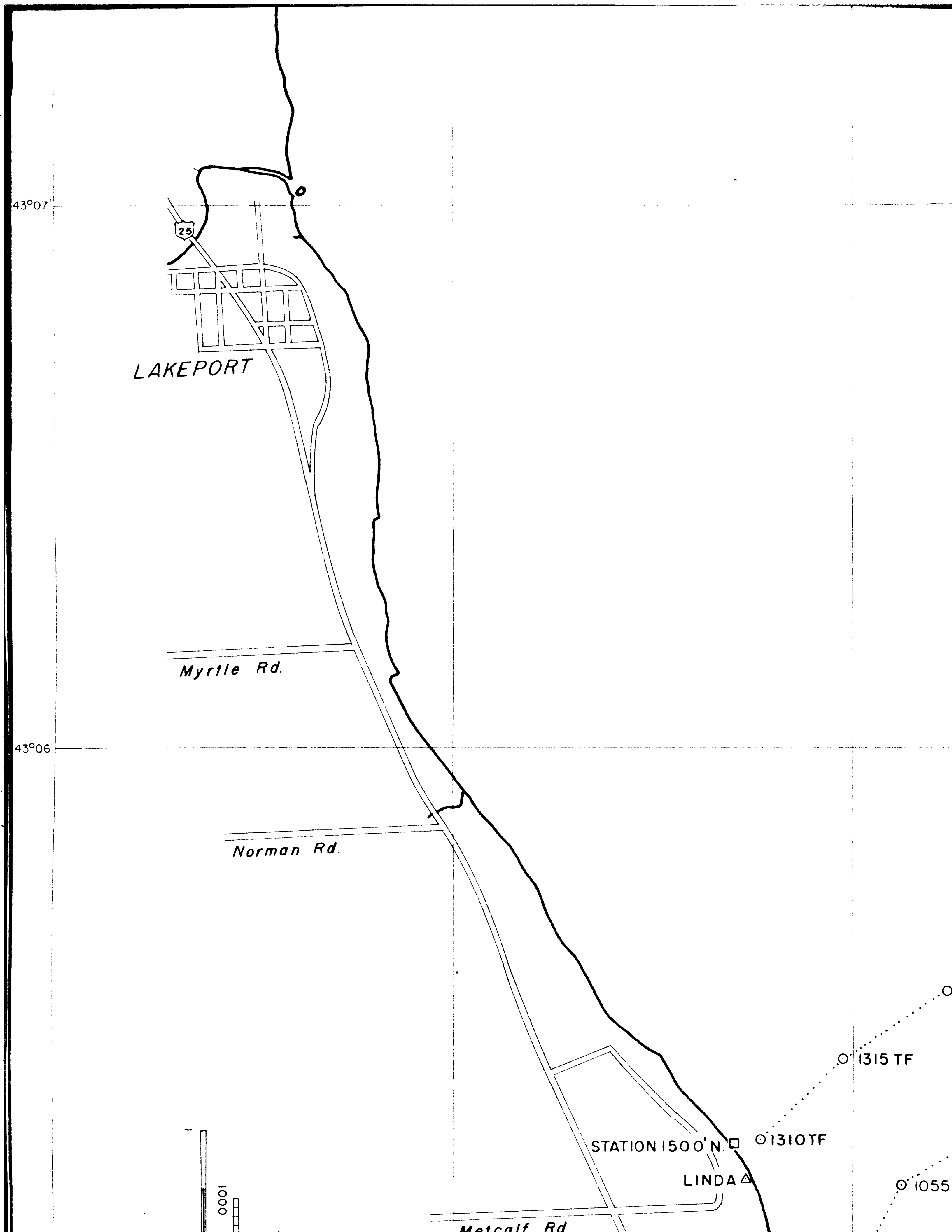
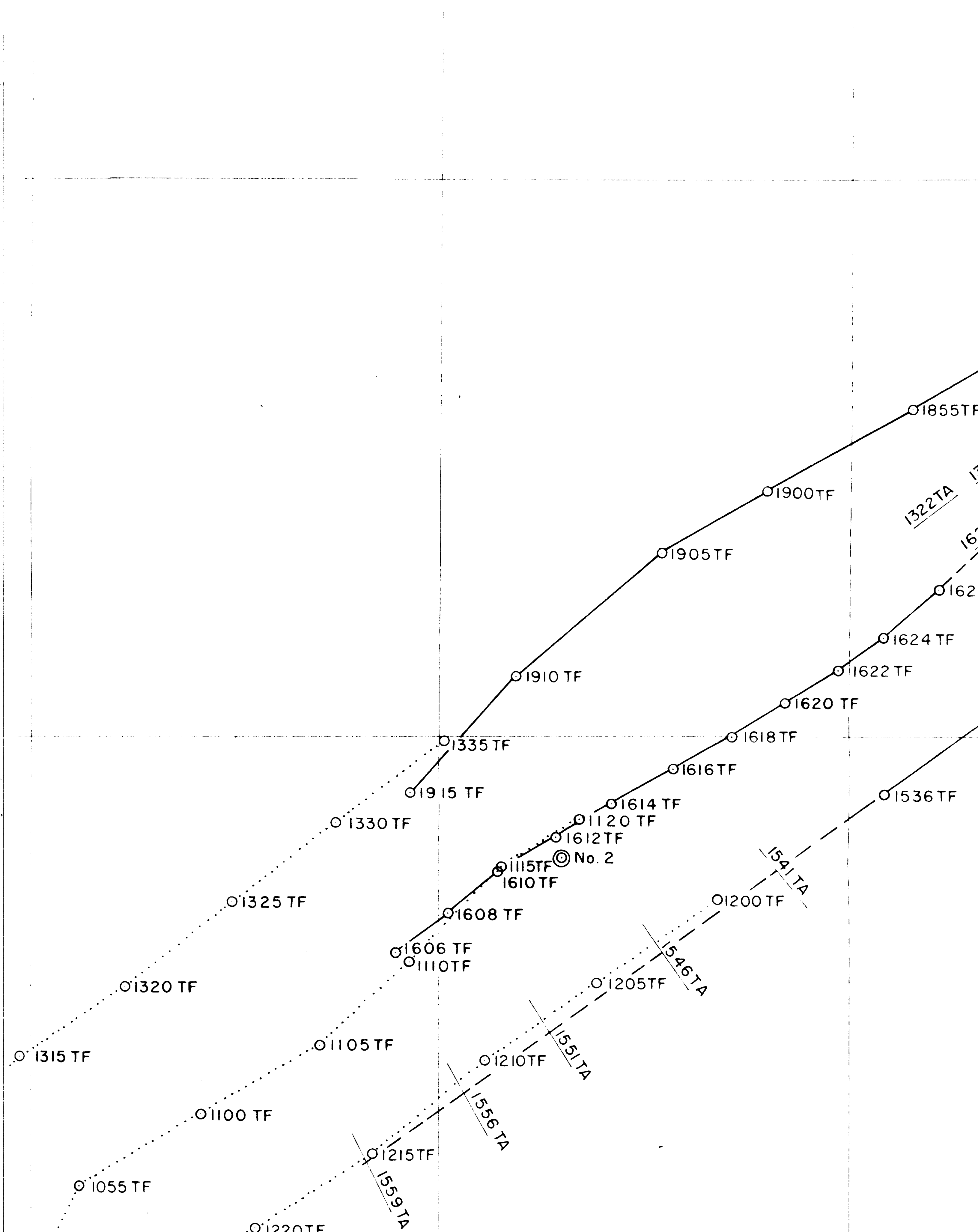

82° 26'
82° 25'
82° 24'
SCALE OF FEET
1000
0
1000
2000
3000
4000
5000
6000
1
3/4
1/2
1/4
0
STATUTE MILES
1830 TF
1810 TF
1825TF

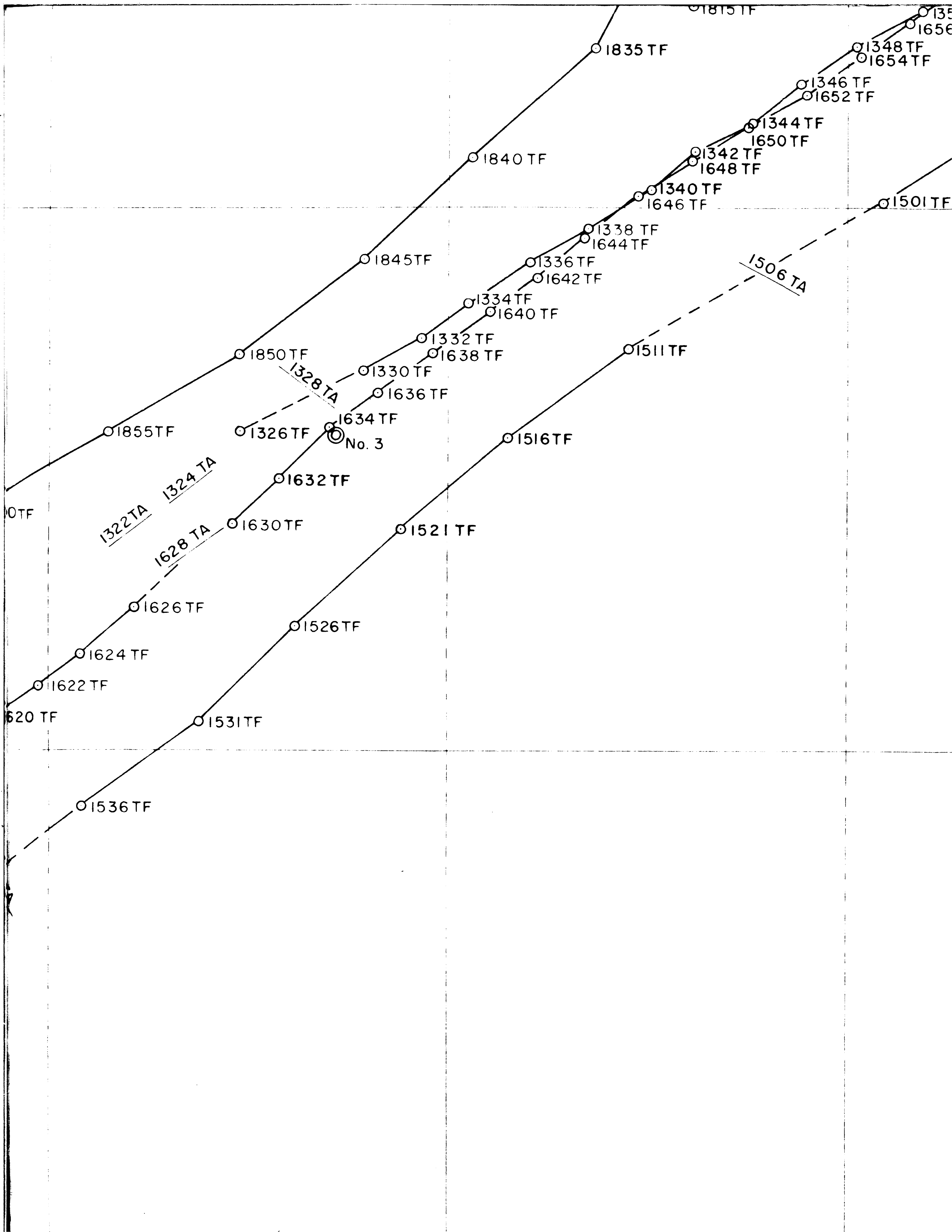
PLATE I


82° 24'
82° 23'
SCALE OF FEET
3000
4000
5000
6000
7000
8000
0
1/2
1
STATUTE MILES
43°09'
43°08'
1750 TF
1755 TF
1800 TF
1805 TF
1810 TF
1830 TF
1825TF
1820 TF
1708-10-12 TA
1404 TF
1402 TF
1400 TF
1706 TF
1358 TF
1704 TF
No. 4
1356 TF
1702 TF
1354 TF
1700 TF
1352 TF

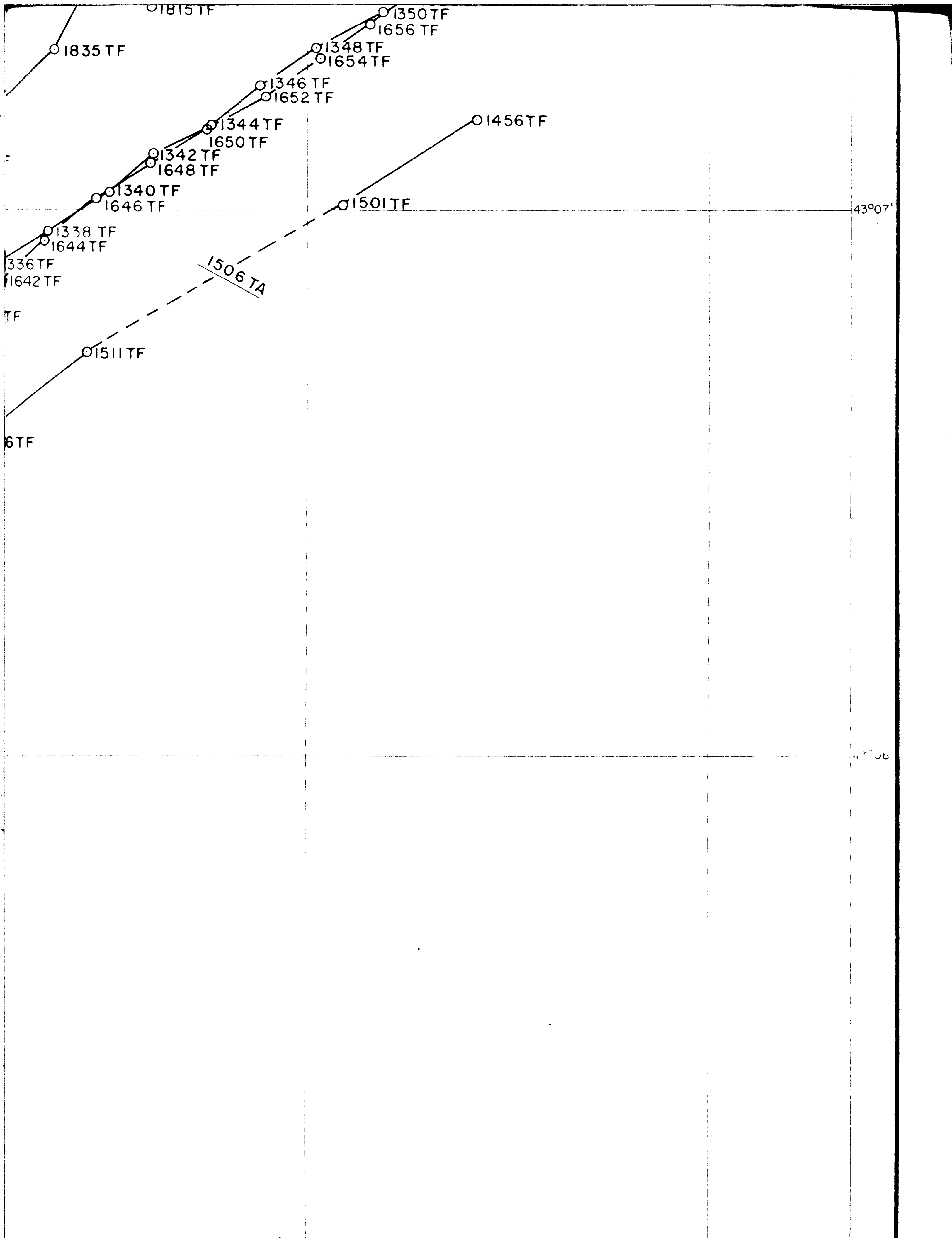


43°07'
25
LAKEPORT
Myrtle Rd.
43°06'
Norman Rd.
1315 TF
STATION 1500'N.
1310 TF
LINDA
1055
1000
Metcalf Rd

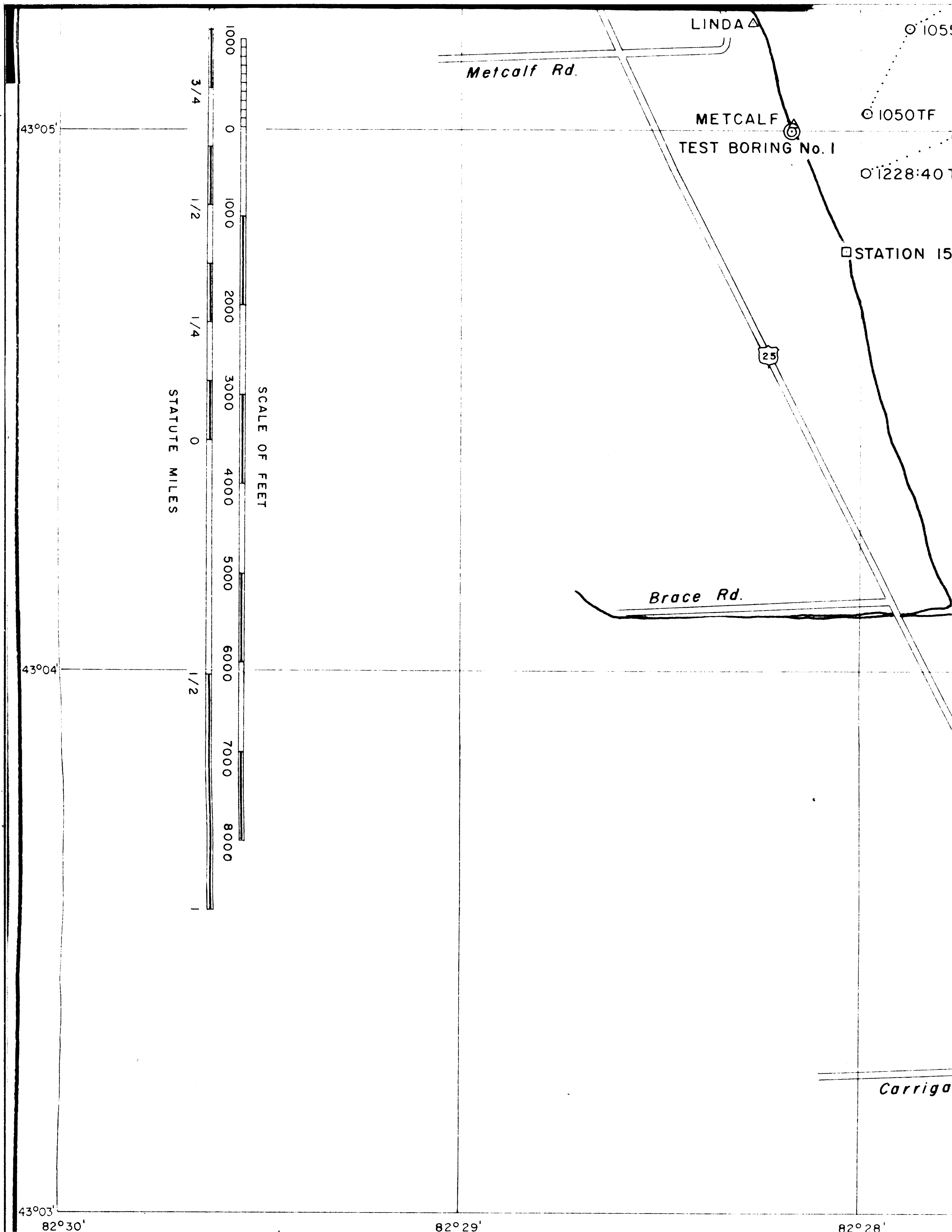

1855 TF
1900 TF
1322 TA
1905 TF
1624 TF
1622 TF
1910 TF
1620 TF
1335 TF
1618 TF
1616 TF
1915 TF
1536 TF
1614 TF
1330 TF
1120 TF
1612 TF
No. 2
1115 TF
1610 TF
1541 TA
1325 TF
1200 TF
1608 TF
1606 TF
1110 TF
1546 TA
1320 TF
1205 TF
1551 TA
1315 TF
1105 TF
1210 TF
1556 TA
1100 TF
1215 TF
1559 TA
1055 TF

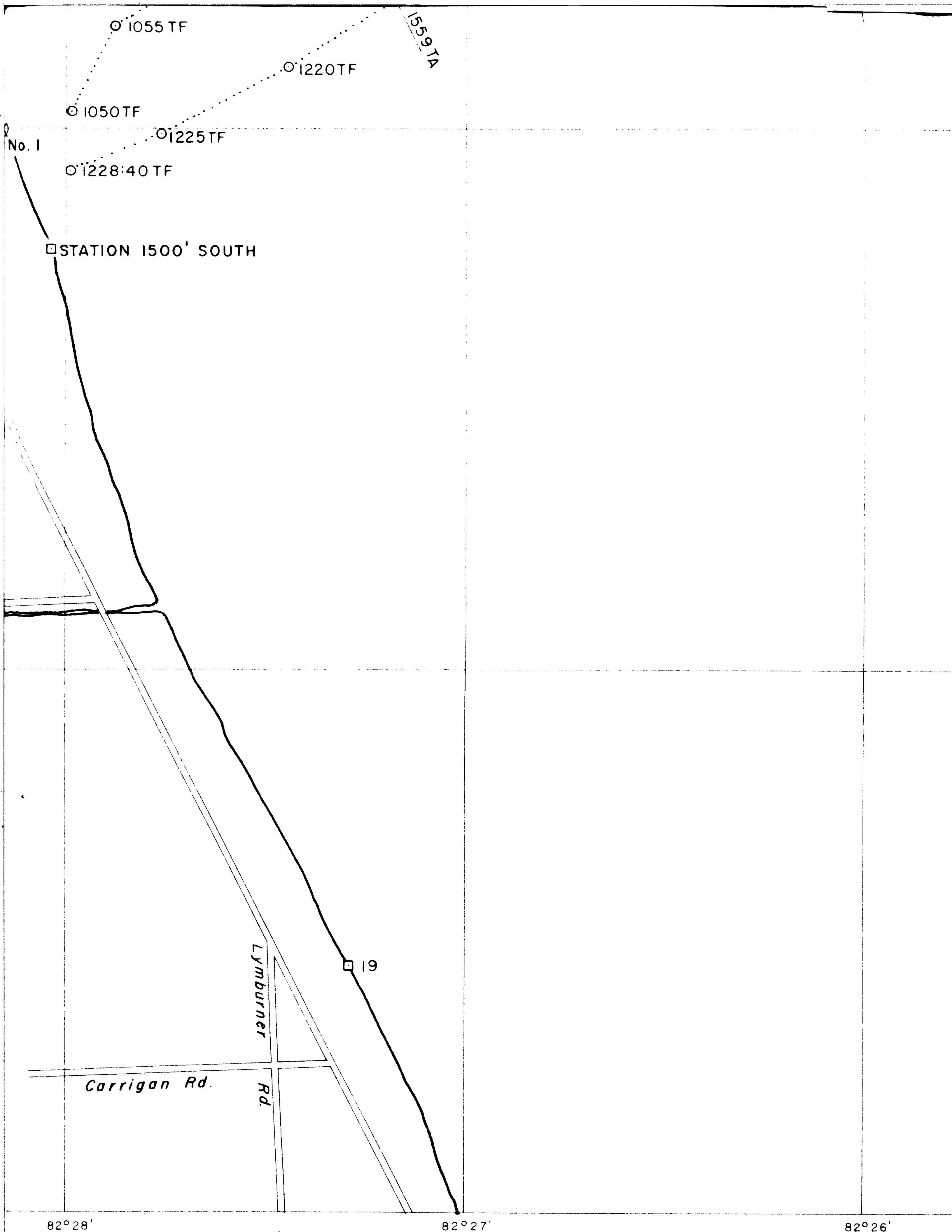


1815 TF
1835 TF
1840 TF
1845TF
1850 TF
1855TF
0TF
135
1656
1348 TF
1654 TF
1346 TF
1652 TF
1344 TF
1650 TF
1342 TF
1648 TF
1340 TF
1646 TF
1338 TF
1644 TF
1336 TF
1642 TF
1334 TF
1640 TF
1332 TF
1638 TF
1330 TF
1636 TF
1634 TF
1328 TA
1326 TF
No. 3
1324 TA
1322 TA
1632 TF
1630 TF
1628 TA
1626 TF
1624 TF
1622 TF
620 TF
1501 TF
1506 TA
1511 TF
1516 TF
1521 TF
1526 TF
1531 TF
1536 TF

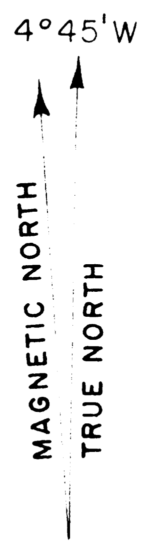


1815 TF
1835 TF
1350 TF
1656 TF
1348 TF
1654 TF
1346 TF
1652 TF
1344 TF
1650 TF
1456 TF
1342 TF
1648 TF
1340 TF
1646 TF
1501 TF
43°07'
1338 TF
1644 TF
1642 TF
1506 TA
1511 TF


LINDA
Metcalf Rd.
METCALF
TEST BORING No. 1
1055
1050TF
1228:40T
STATION 15
25
Brace Rd.
Carriga
43°05'
43°04'
43°03'
82°30'
82°29'
82°28'
SCALE OF FEET
1000
0
1000
2000
3000
4000
5000
6000
7000
8000
STATUTE MILES
3/4
1/2
1/4
0
1/2
1



1055 TF
1559 TA
1220 TF
1050 TF
No. 1
1225 TF
1228:40 TF
STATION 1500' SOUTH
19
Lymburner
Rd.
Carrigan Rd.
82°28'
82°27'
82°26'



CITY OF DETROIT

DEPARTMENT OF WATER

LAKE HURON WATER SUPPL

CONTINUOUS SEISMIC PROFILING

1962

SCALE 1: 15,000

EXPLANATION

- ⊙ TF= TRANSIT FIX (TIME OF S
- —— TA = TRANSIT ANGLE
- ——— = TRACK OF R/V INLAND
- ········ = TRACK OF DWS BOAT
- – – – – = ESTIMATED TRACK
- △ = TRIANGULATION STATI
- ⊡ = LOW ORDER STATION
- ◎ = LOCATION OF TEST BO

✱ NOTE THAT THE BASE
CHIEFLY FROM U.S. LAK
CHART LS 511

82°26'   82°25'

43°05'

CITY OF DETROIT
DEPARTMENT OF WATER SUPPLY
:E HURON WATER SUPPLY PROJECT

JUOUS SEISMIC PROFILING TRAVERSES
1962

SCALE 1: 15,000

43°04'

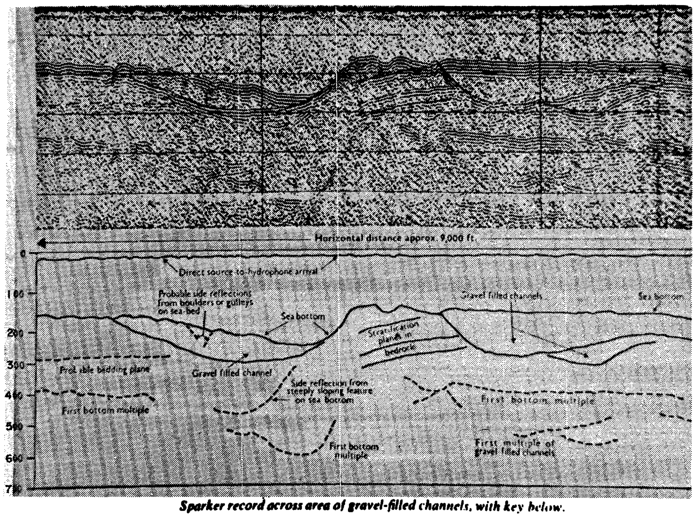
EXPLANATION

= TRANSIT FIX (TIME OF SHIP'S POSITION)
= TRANSIT ANGLE
= TRACK OF R/V INLAND SEAS
= TRACK OF DWS BOAT
= ESTIMATED TRACK
= TRIANGULATION STATION
= LOW ORDER STATION
= LOCATION OF TEST BORING

NOTE THAT THE BASE WAS TAKEN CHIEFLY FROM U.S. LAKE SURVEY CHART LS 511

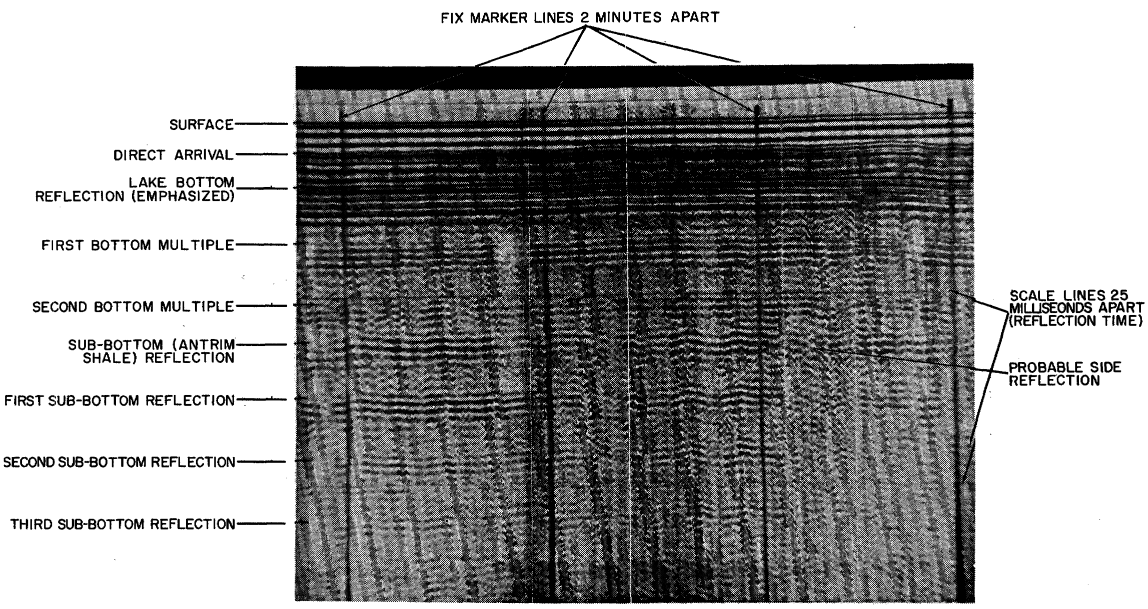
43°03'

PLATE 2



Sparker record across area of gravel-filled channels, with key below.

A. EXAMPLE OF SPARKER RECORD FROM BECKMANN, W.C. (1960).



B. RECORD ILLUSTRATING TYPICAL FEATURES. (ENLARGED 1-1/2 TIMES).

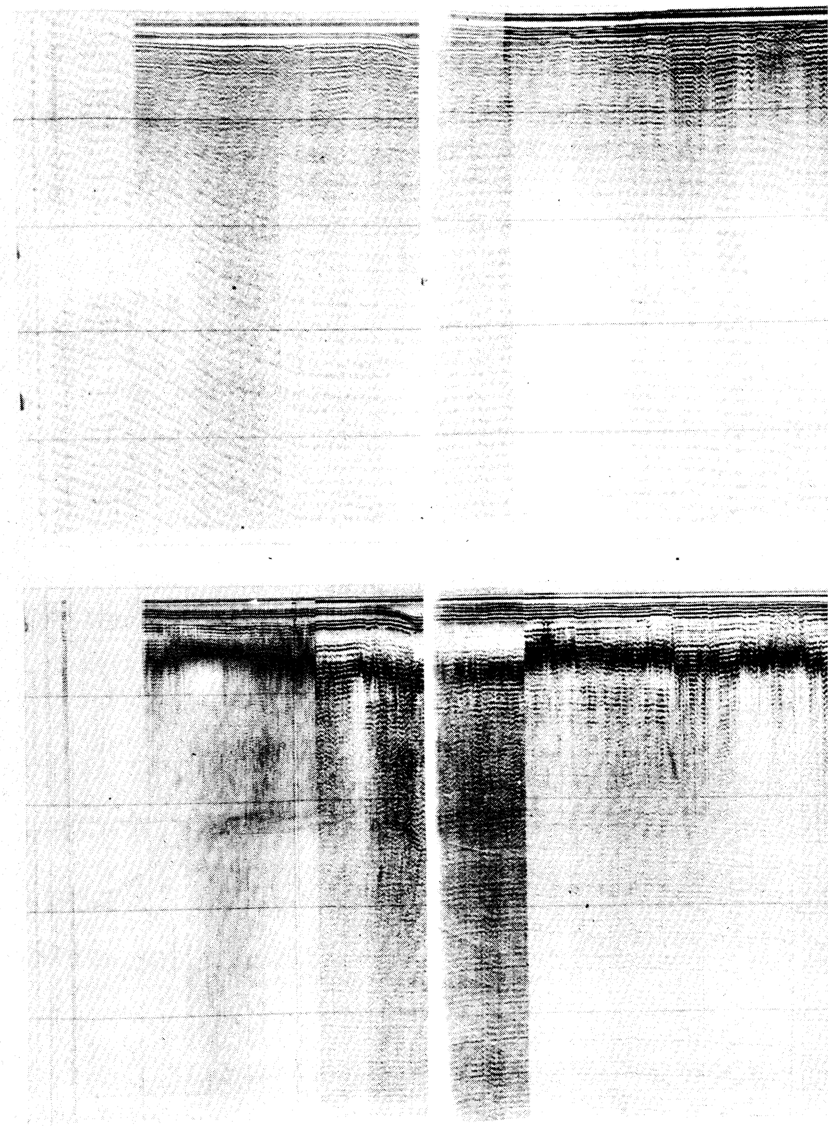
Detroit Water Supply Project
Lake Huron
Near Shore Runs

27 July 1962

Recorded on Dept of Water Supply
work boat <u>WATER</u> <u>LILY</u> (code name)

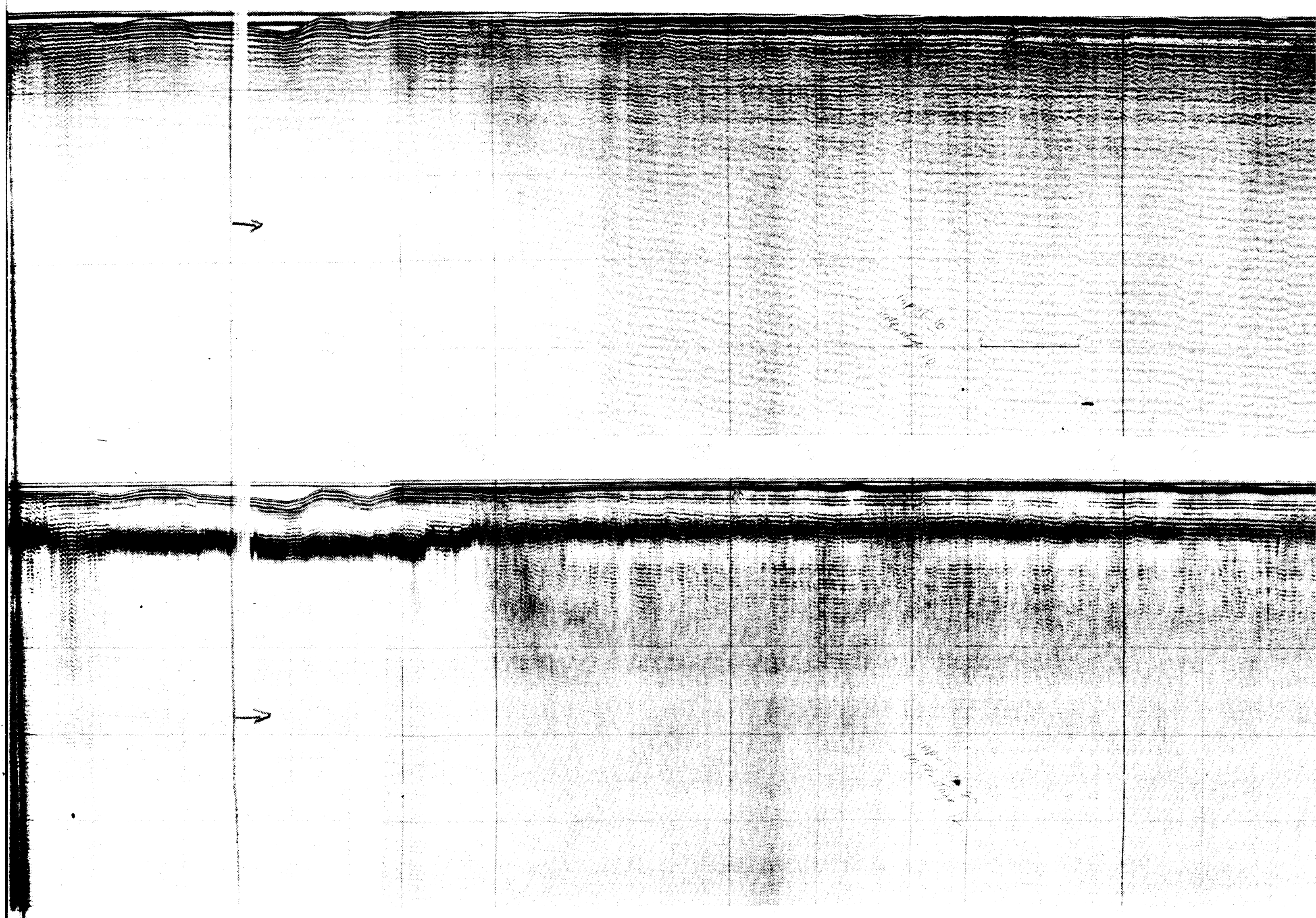
Two generators to power equipment
1000 watt – instruments
2000 watt – Spark source

Metcalf Range

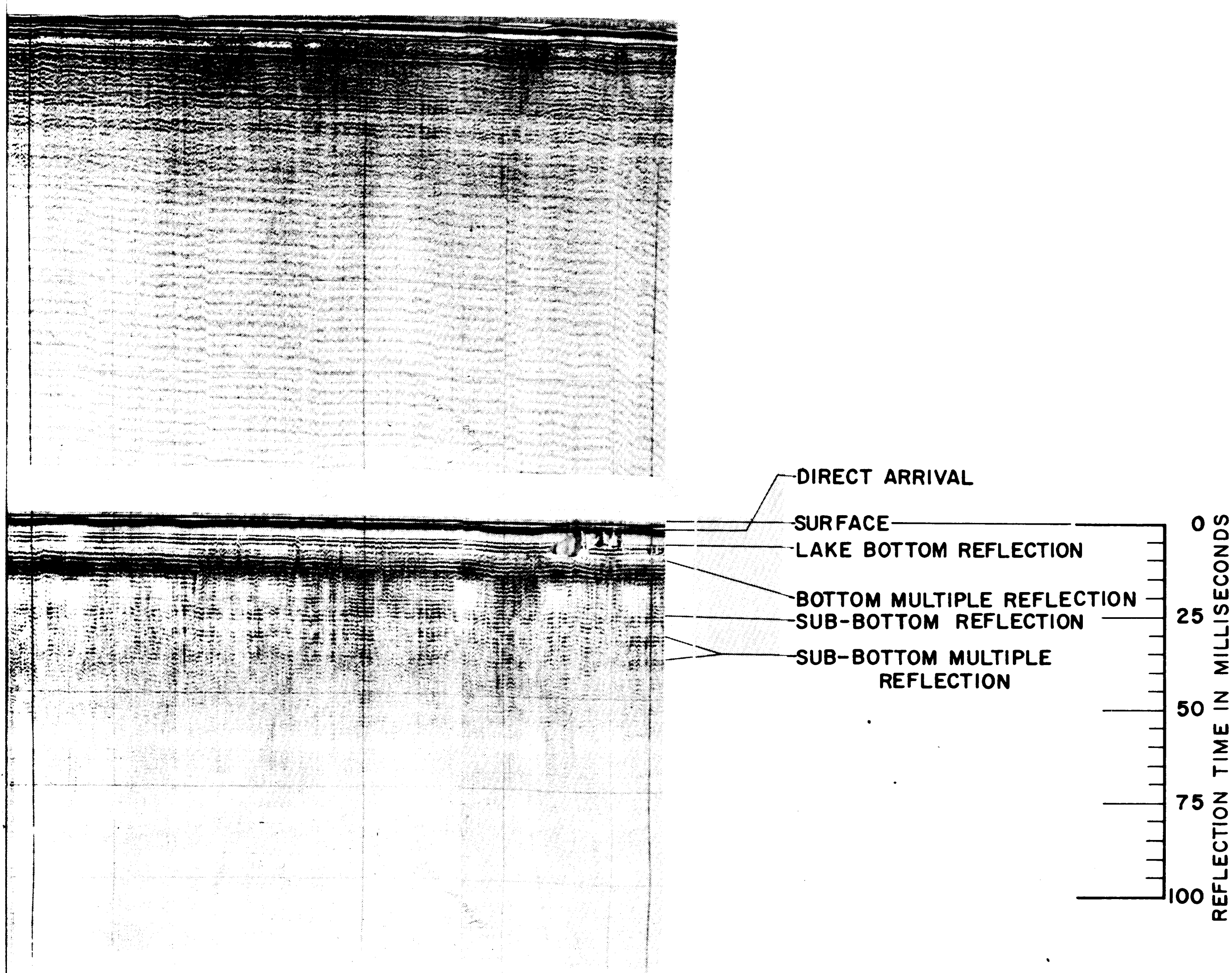


METCALF
JUL

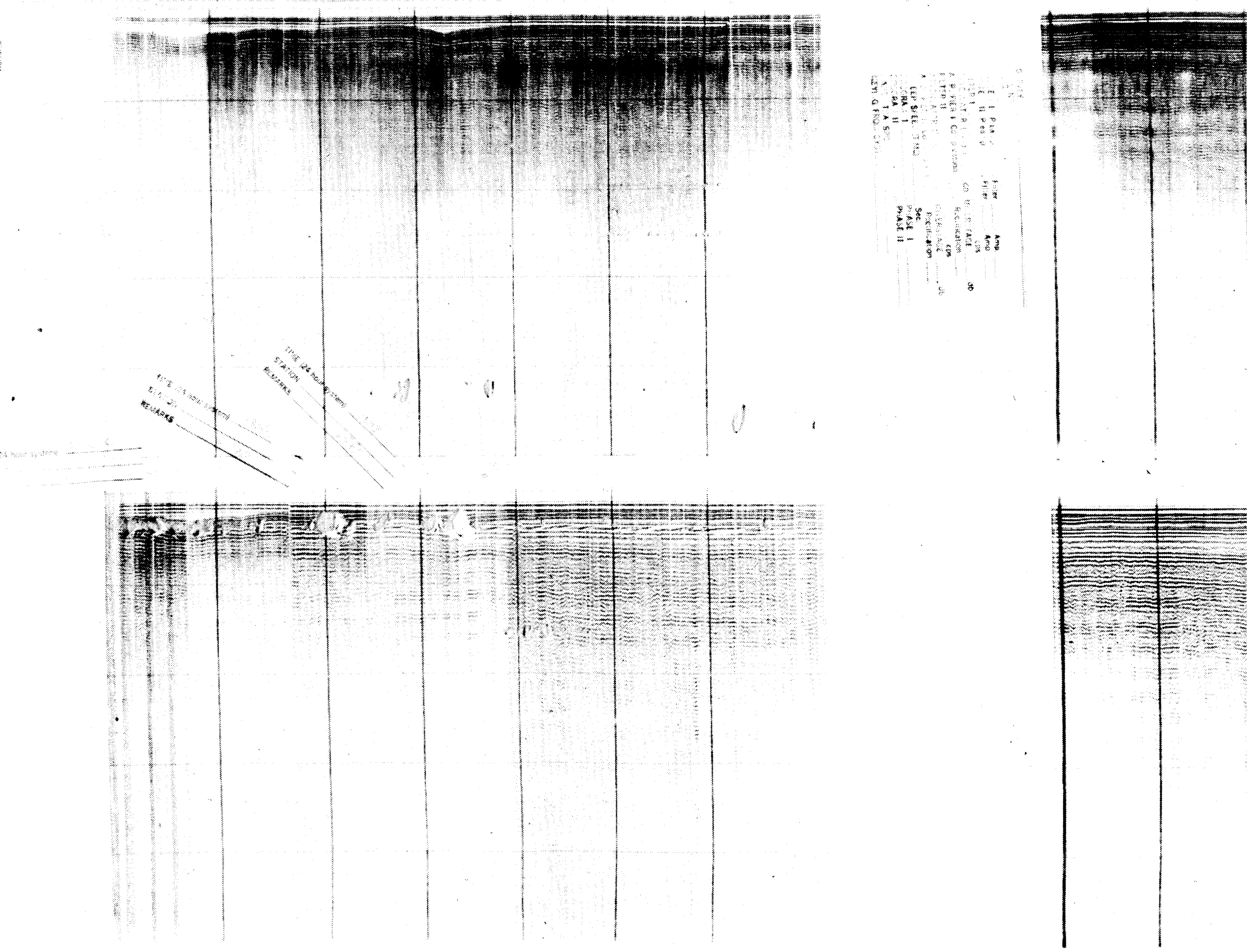
PLATE 3



CALF TRAVERSE, SOUTH END OF LAKE HURON —— 10 50 TF TO 11 21 TF
JULY 27, 1962 —— DETROIT DEPARTMENT OF WATER SUPPLY BOAT


DIRECT ARRIVAL
SURFACE
LAKE BOTTOM REFLECTION
BOTTOM MULTIPLE REFLECTION
SUB-BOTTOM REFLECTION
SUB-BOTTOM MULTIPLE REFLECTION
0
25
50
75
100
REFLECTION TIME IN MILLISECONDS

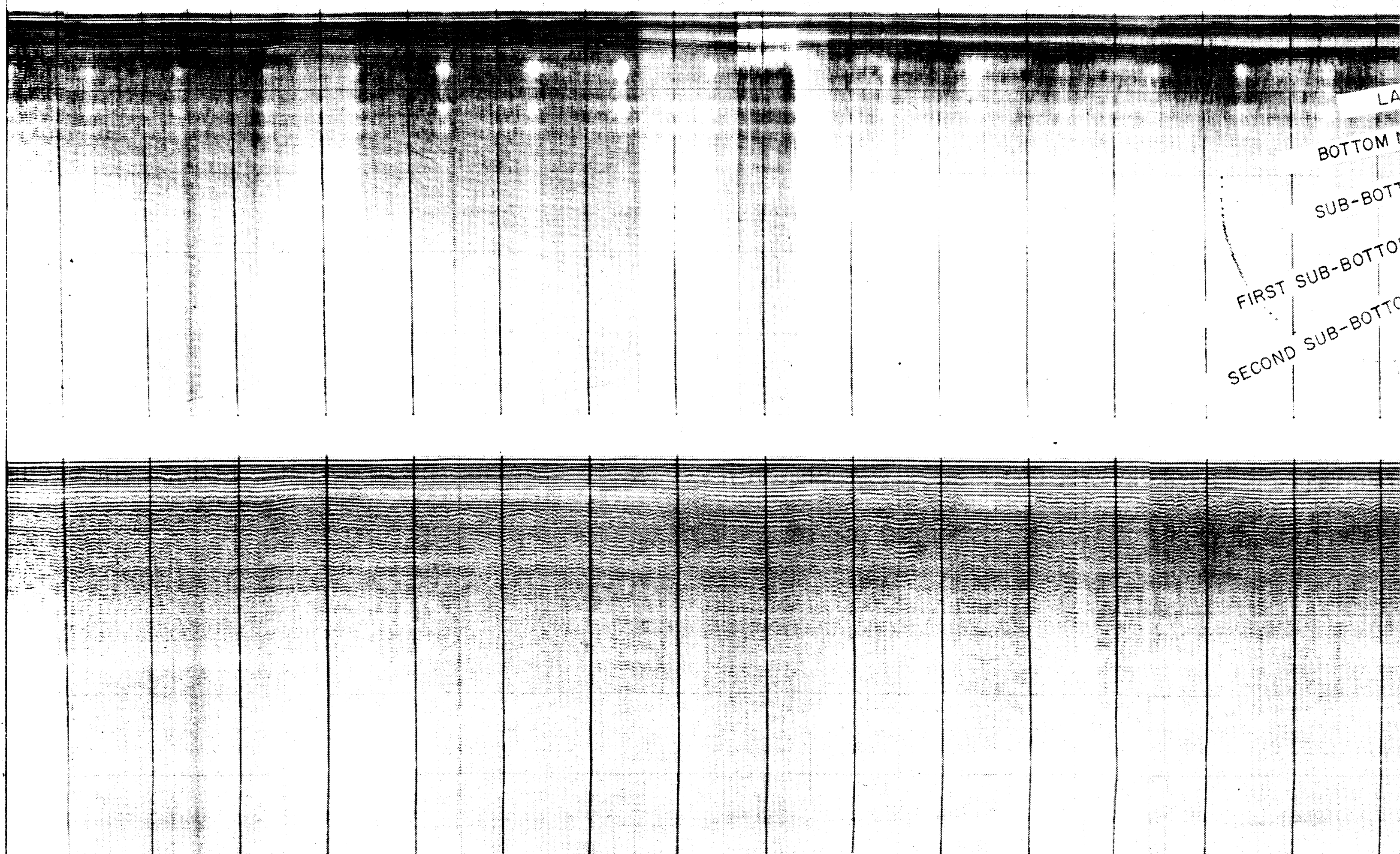
21 TF



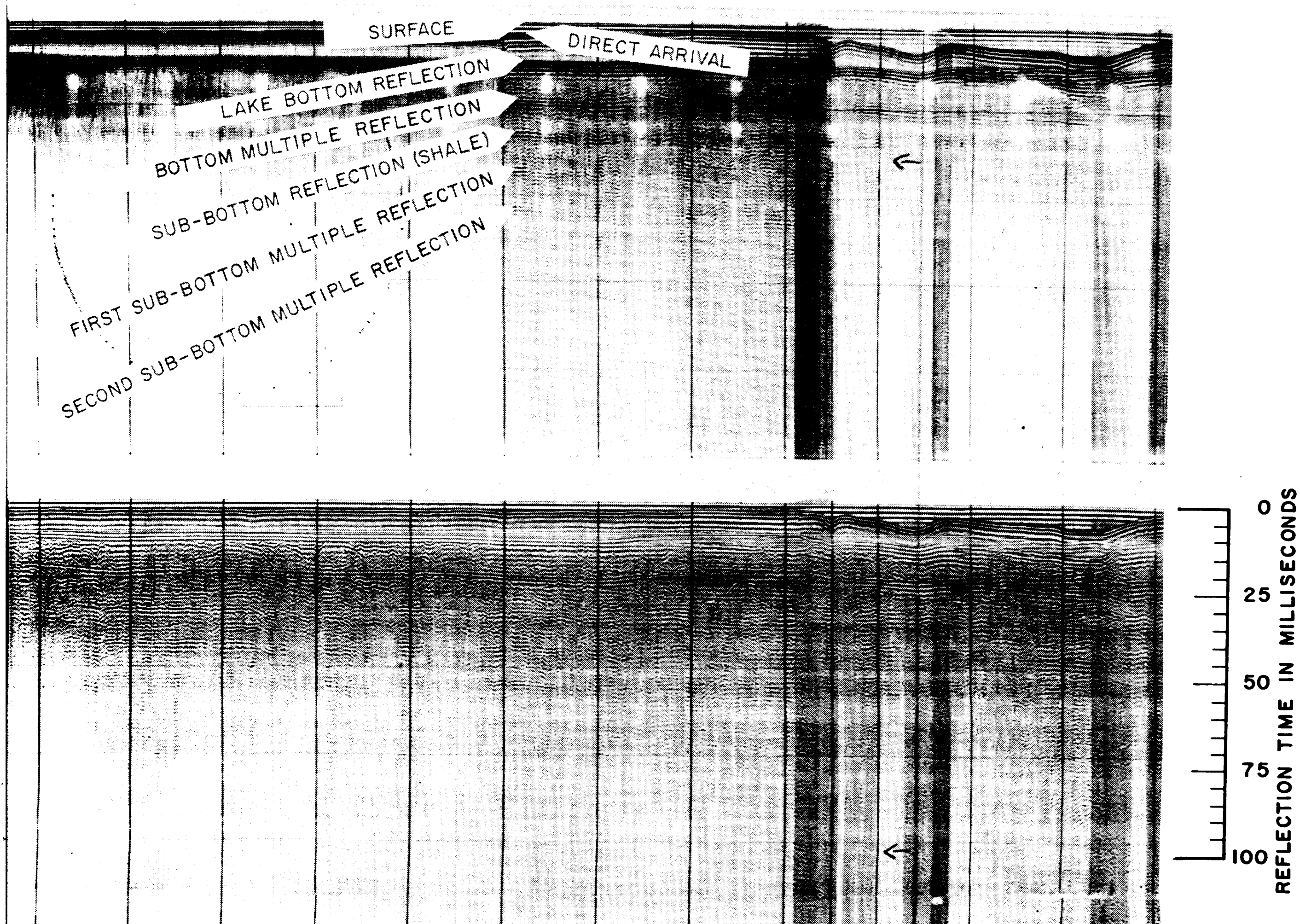
First
MeTcalf
Range
24 July

FIRST

PLATE 4



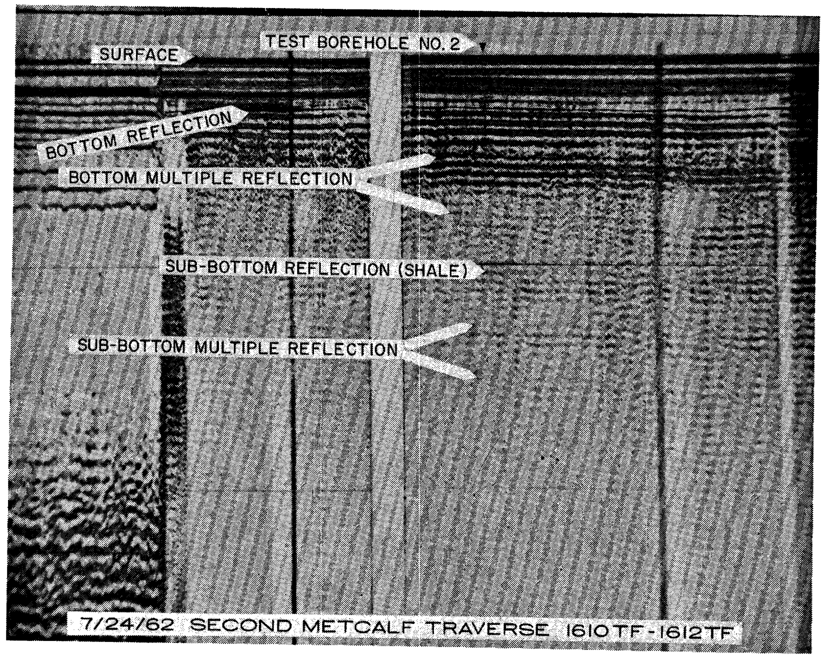
ST METCALF TRAVERSE, SOUTH END OF LAKE HURON —— 13 04 45 TO 14 10
JULY 24, 1962 —— R/V INLAND SEAS

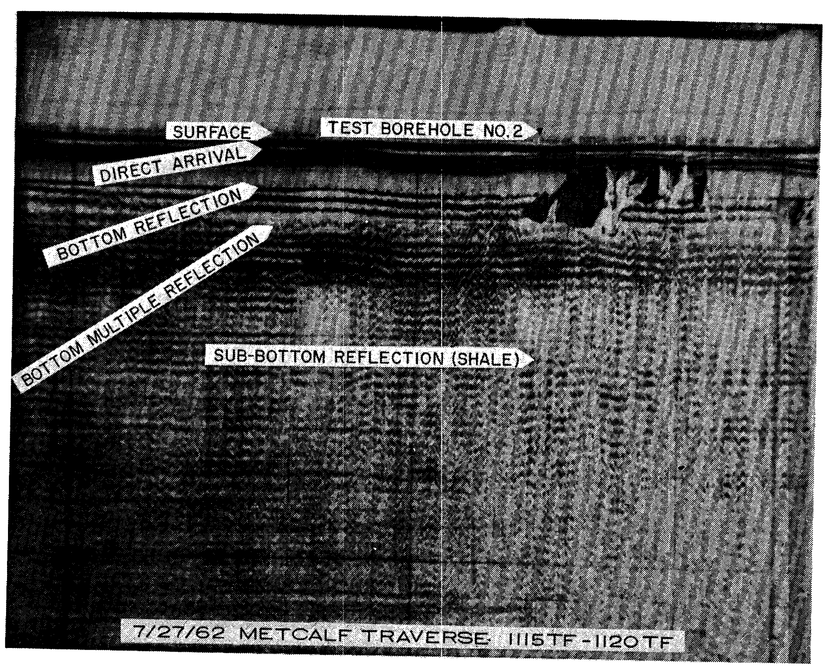


SURFACE
DIRECT ARRIVAL
LAKE BOTTOM REFLECTION
BOTTOM MULTIPLE REFLECTION
SUB-BOTTOM REFLECTION (SHALE)
FIRST SUB-BOTTOM MULTIPLE REFLECTION
SECOND SUB-BOTTOM MULTIPLE REFLECTION
0
25
50
75
100
REFLECTION TIME IN MILLISECONDS

14 10

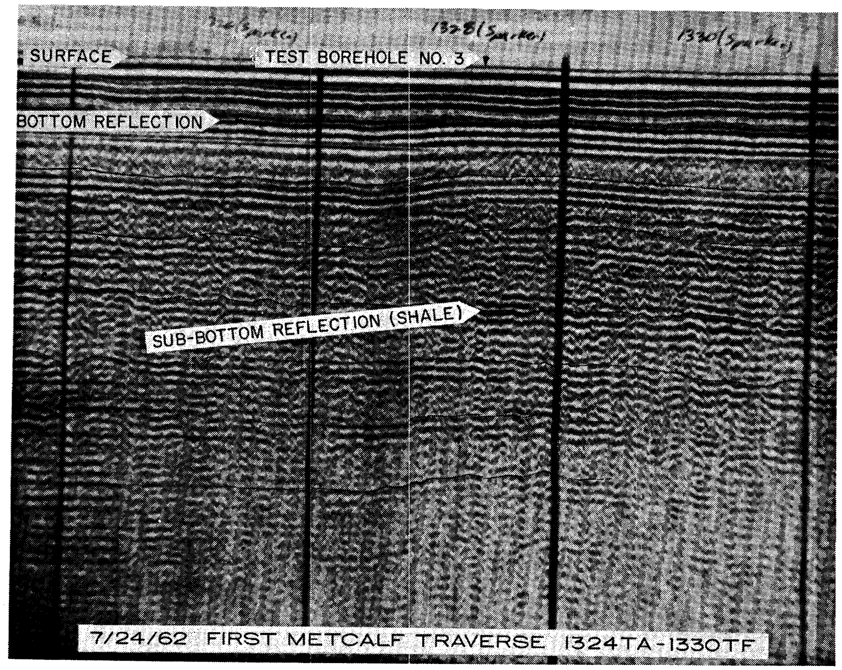
PLATE 5



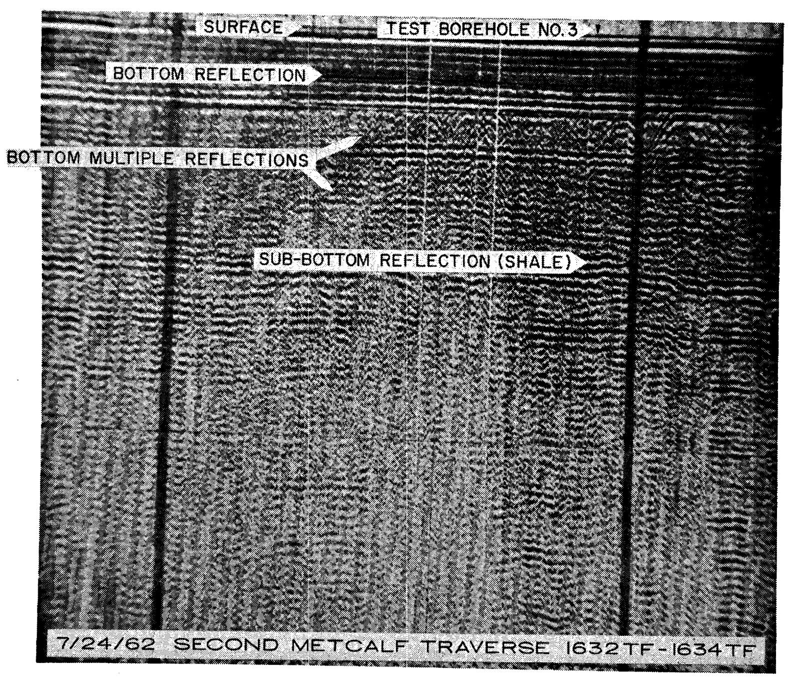


SPARKER RECORDS AT LOCATION OF TEST BOREHOLE NO. 2

PLATE 6



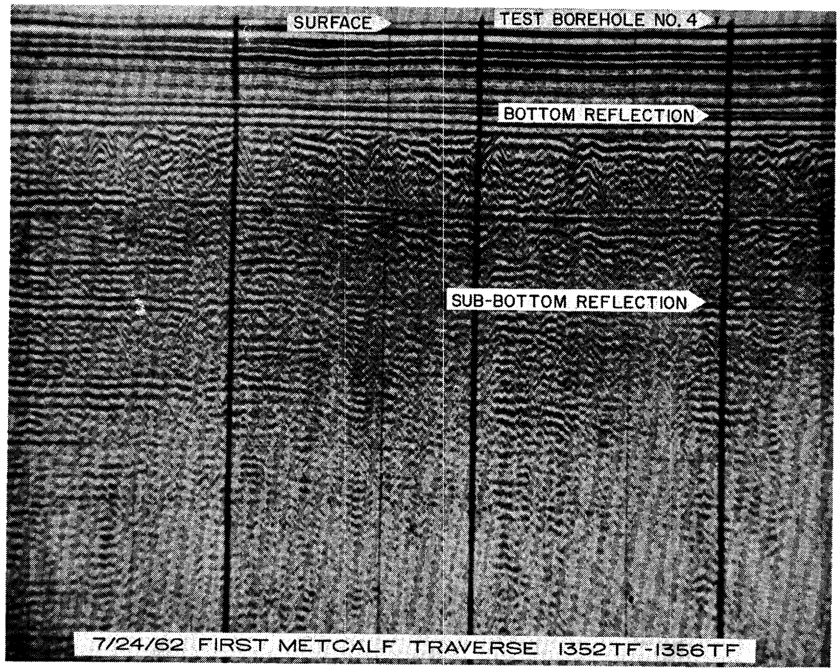
7/24/62 FIRST METCALF TRAVERSE 1324TA-1330TF

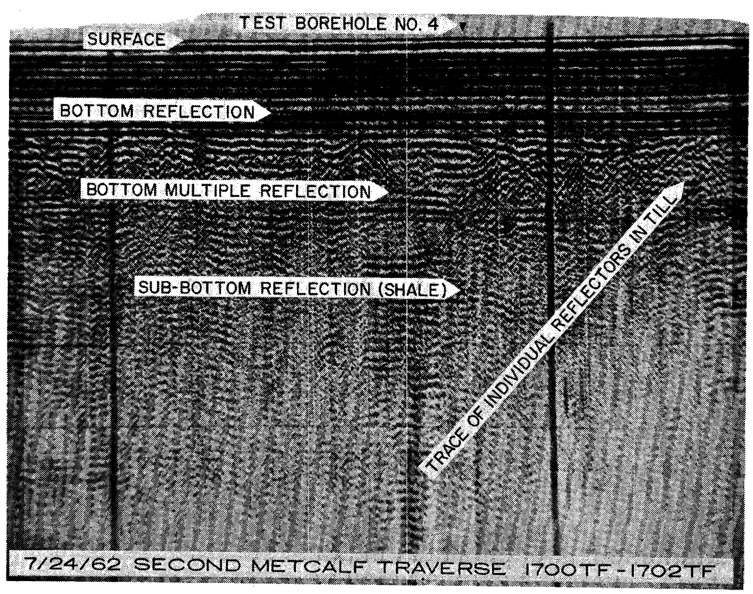


7/24/62 SECOND METCALF TRAVERSE 1632TF-1634TF

SPARKER RECORDS AT LOCATION OF TEST BOREHOLE NO. 3

PLATE 7





SPARKER RECORDS AT LOCATION OF TEST BOREHOLE NO. 4

PLATE NO.8

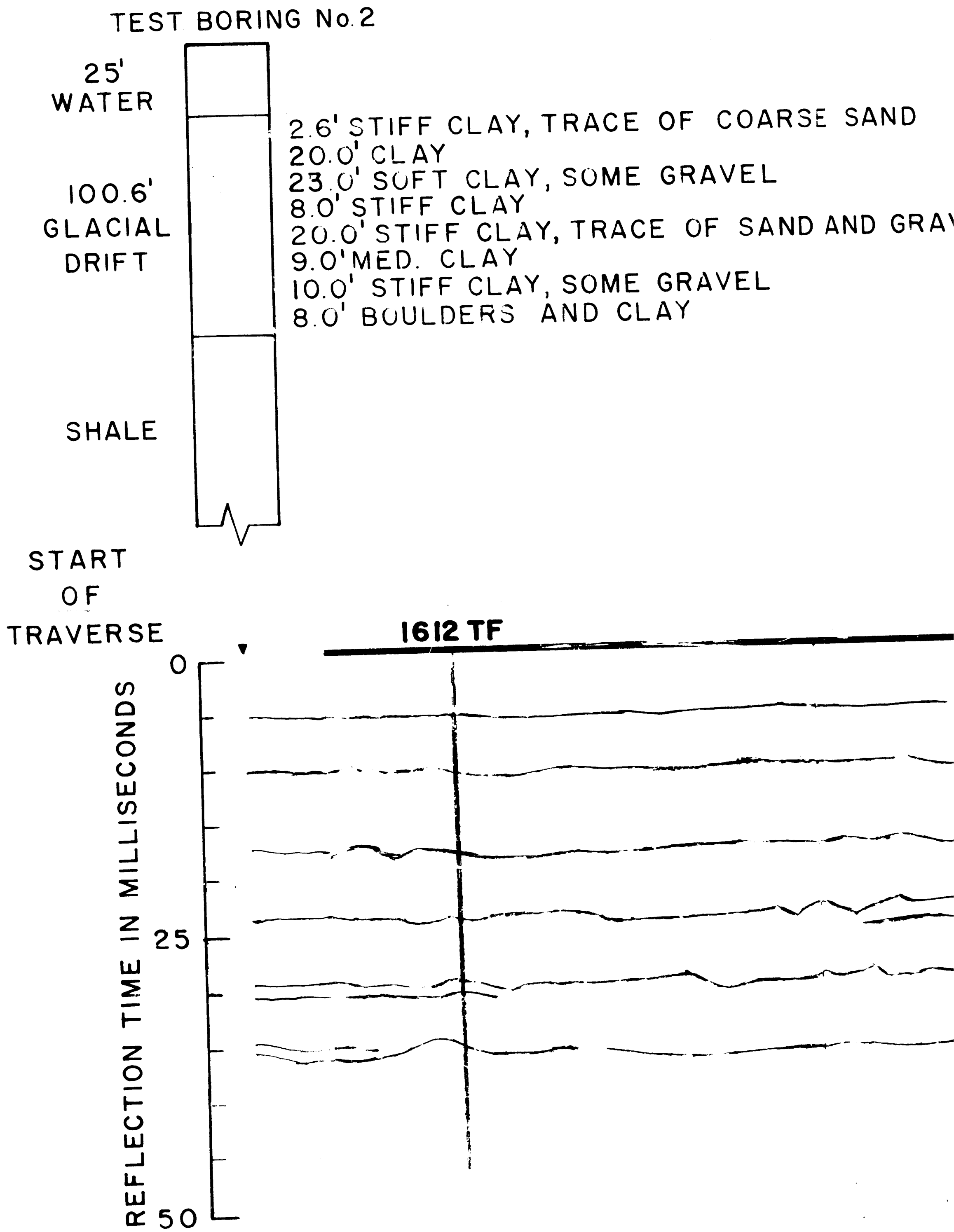
GENERALIZED SKETCH OF REFLECTING HORIZONS SECOND METCALF TRAVERSE, SOUTH END OF LAK JULY 24,1962 – R/V INLAND SEAS

Vertical marker lines denote time of transit fix of ship's position
Horizontal scale varies with ship speed
Logs of test boring from Detroit Water Supply Log of test borings, lower end of Lake Huron, Contract CH-1. Logs are plotted with variable depth scale to agree with continuous seismic profiler records

NOTE: Variable Depth Scale

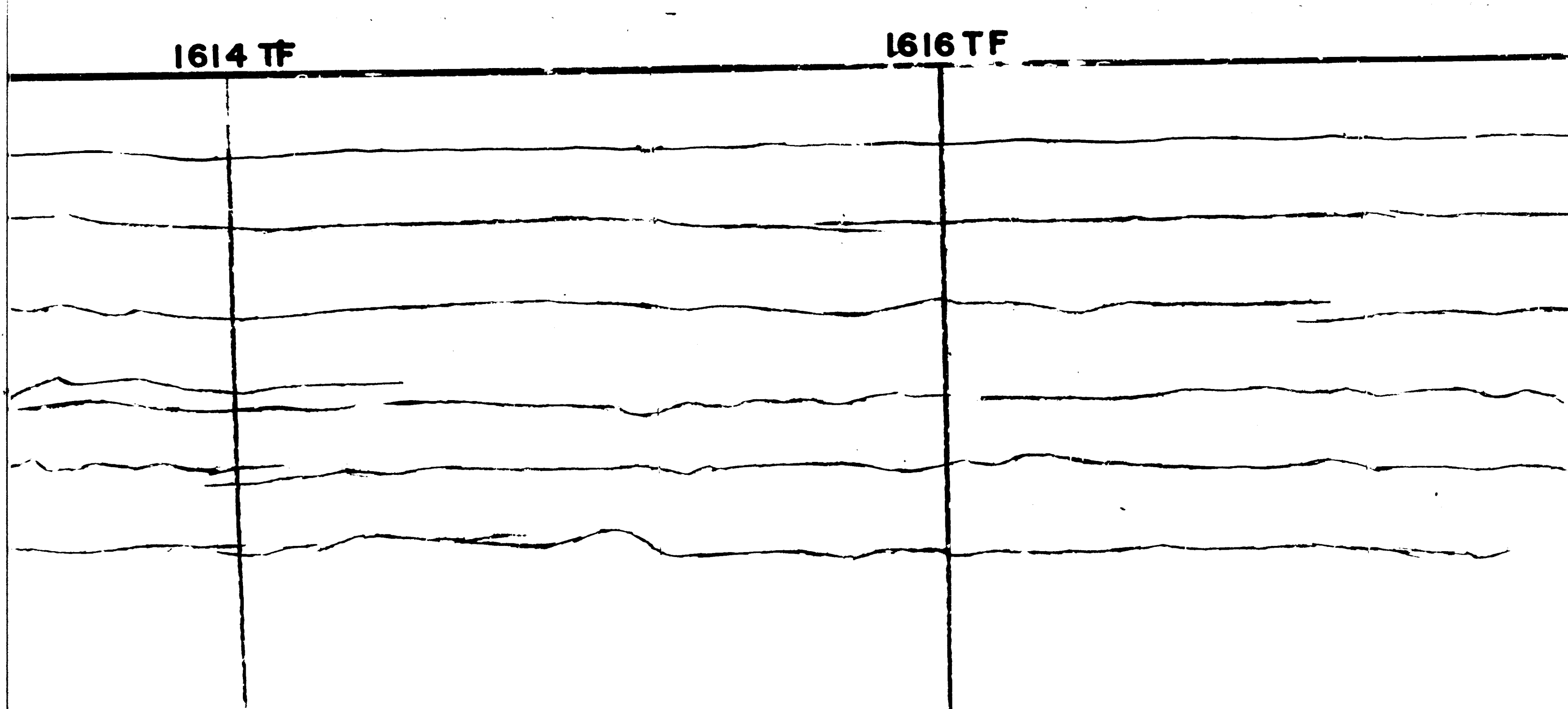
Water	1 inch =	69.3 ft.
Glacial Drift	1 inch =	72.3 ft.
Antrim Shale	1 inch =	114.0 ft.

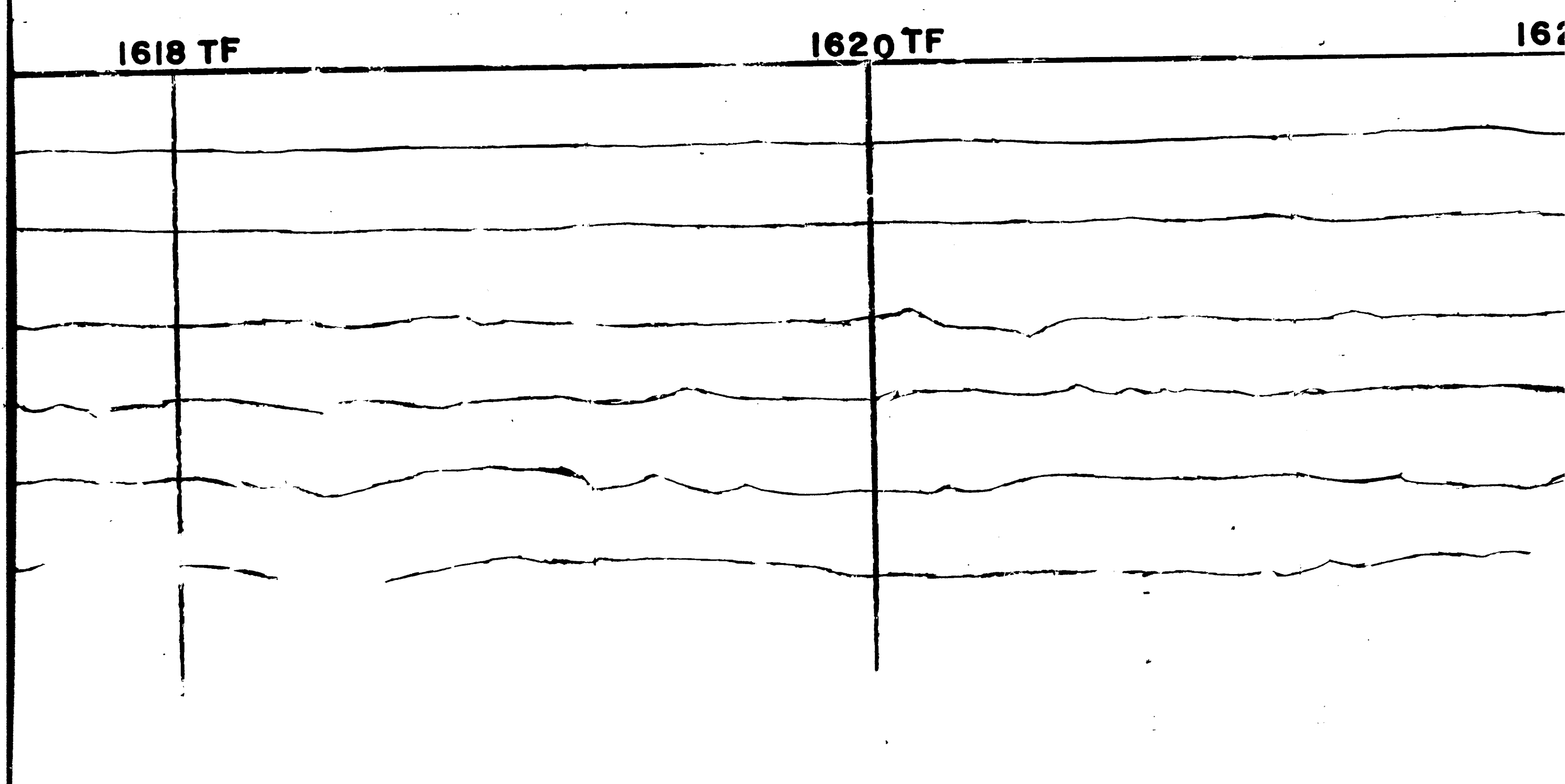
NS
LAKE HURON

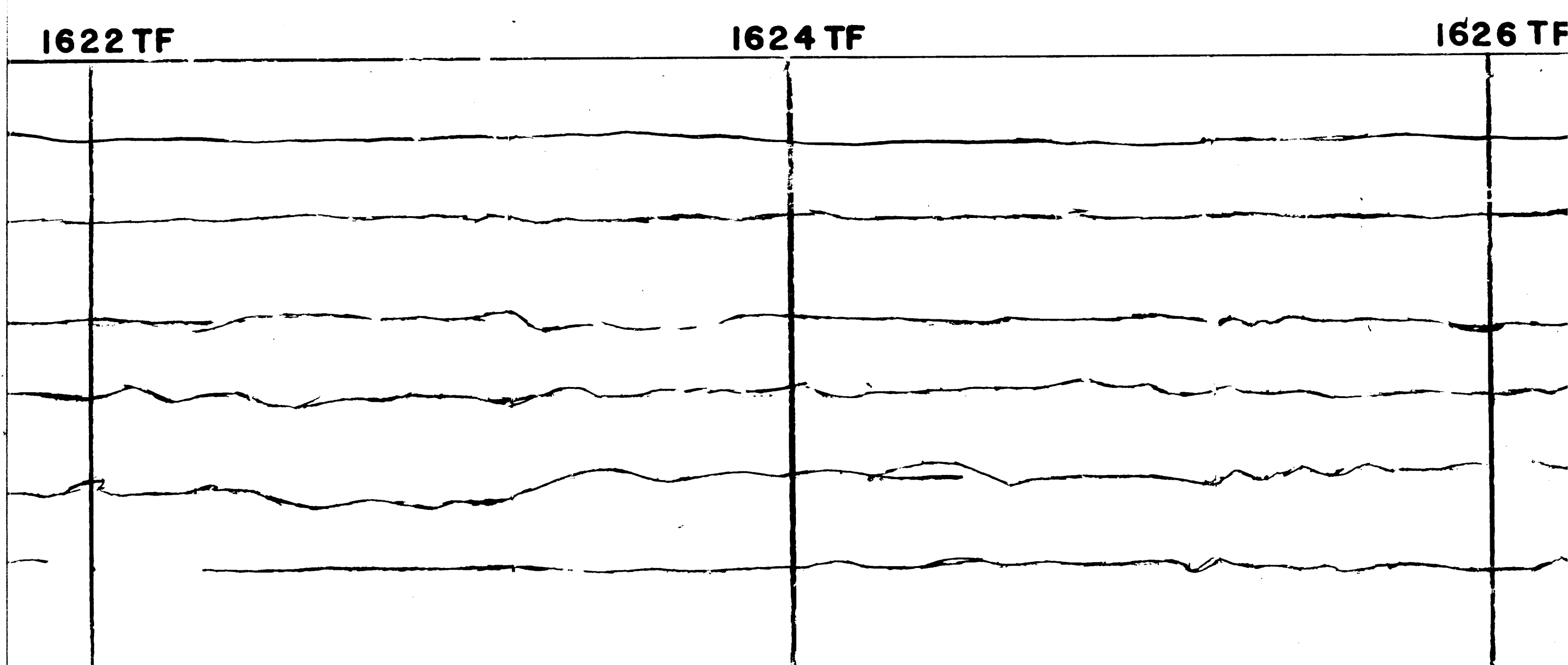


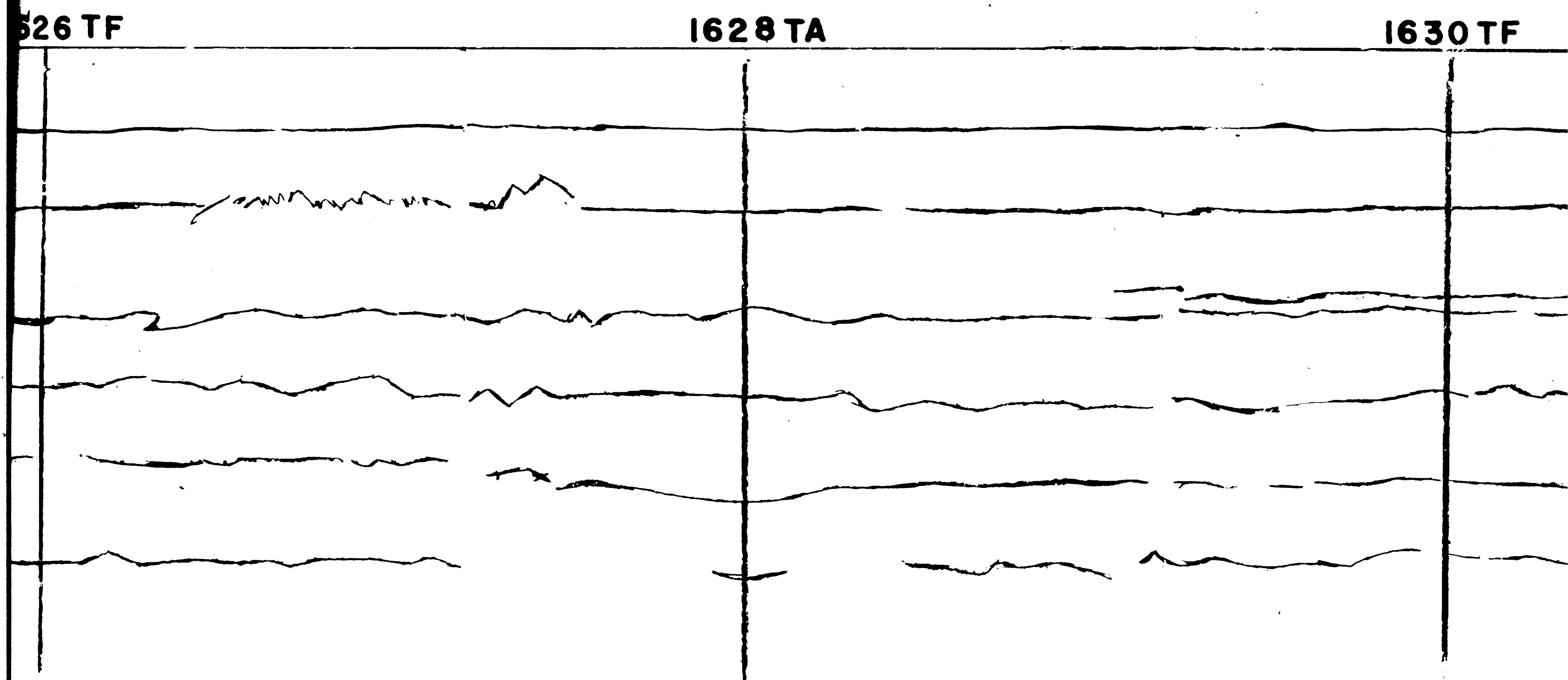
SAND

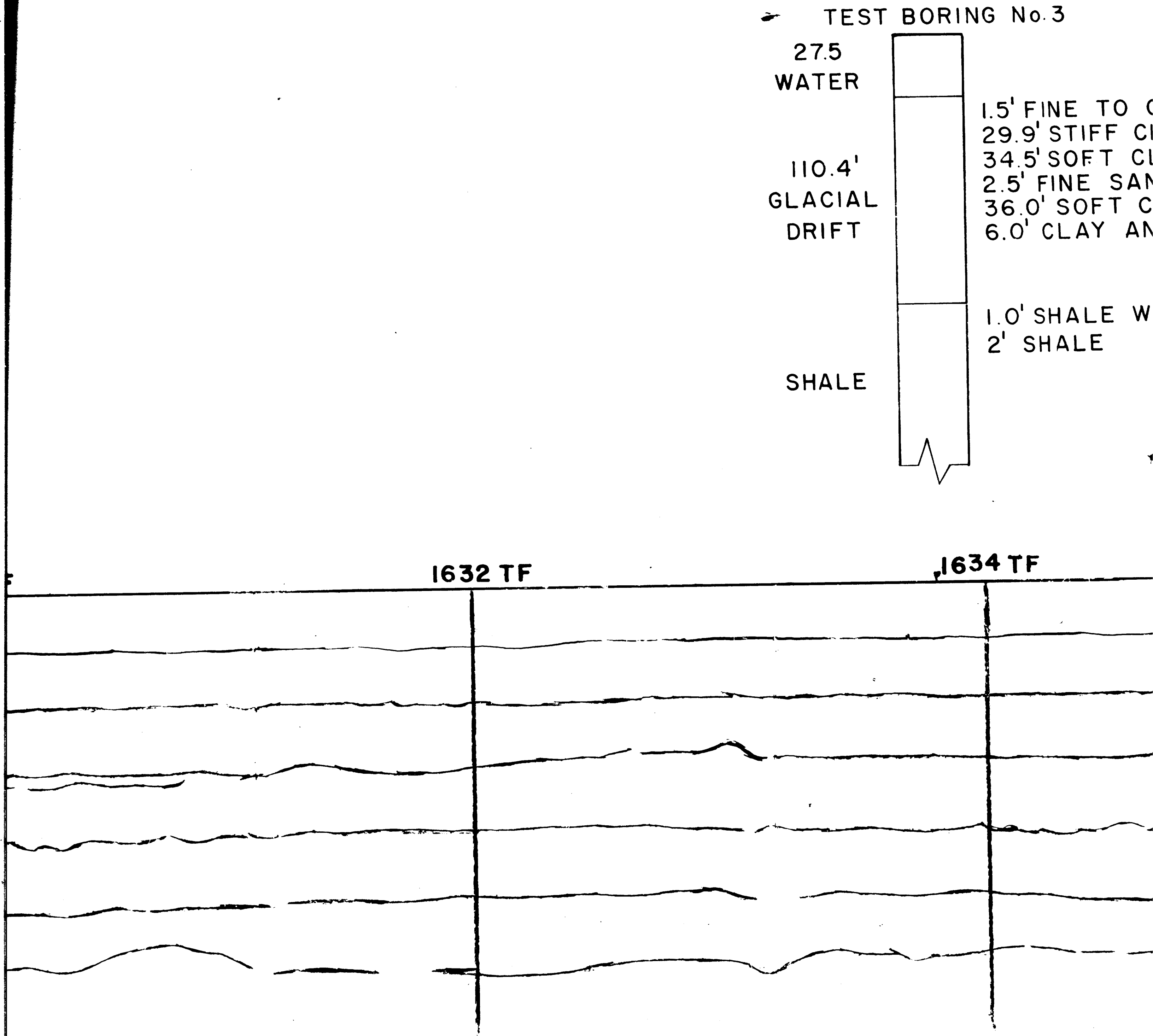
ND GRAVEL




1618 TF
1620 TF


1622 TF
1624 TF
1626 TF


526 TF
1628 TA
1630 TF

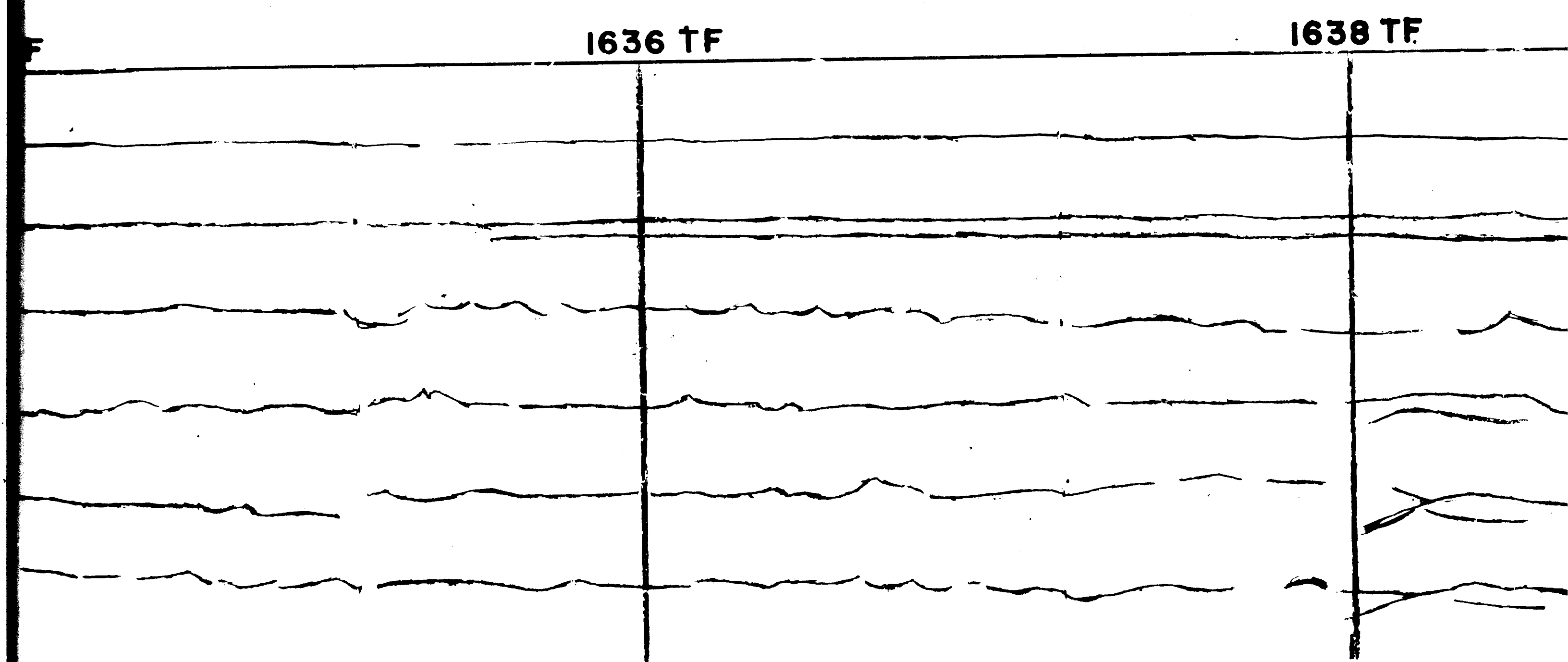


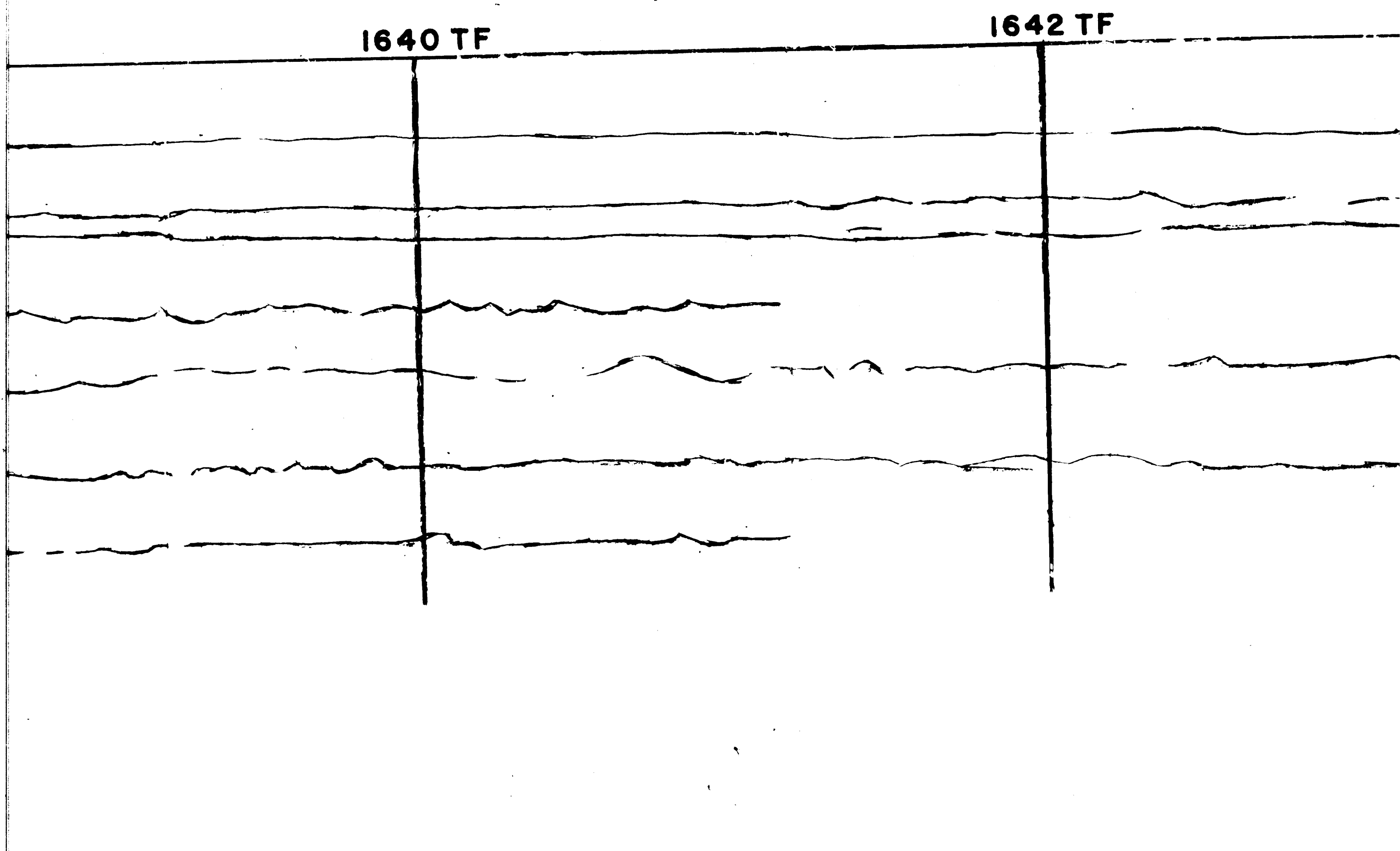
TEST BORING No. 3
27.5
WATER
110.4'
GLACIAL
DRIFT
SHALE
1.5' FINE TO
29.9' STIFF C
34.5' SOFT C
2.5' FINE SA
36.0' SOFT C
6.0' CLAY A
1.0' SHALE W
2' SHALE
1632 TF
1634 TF

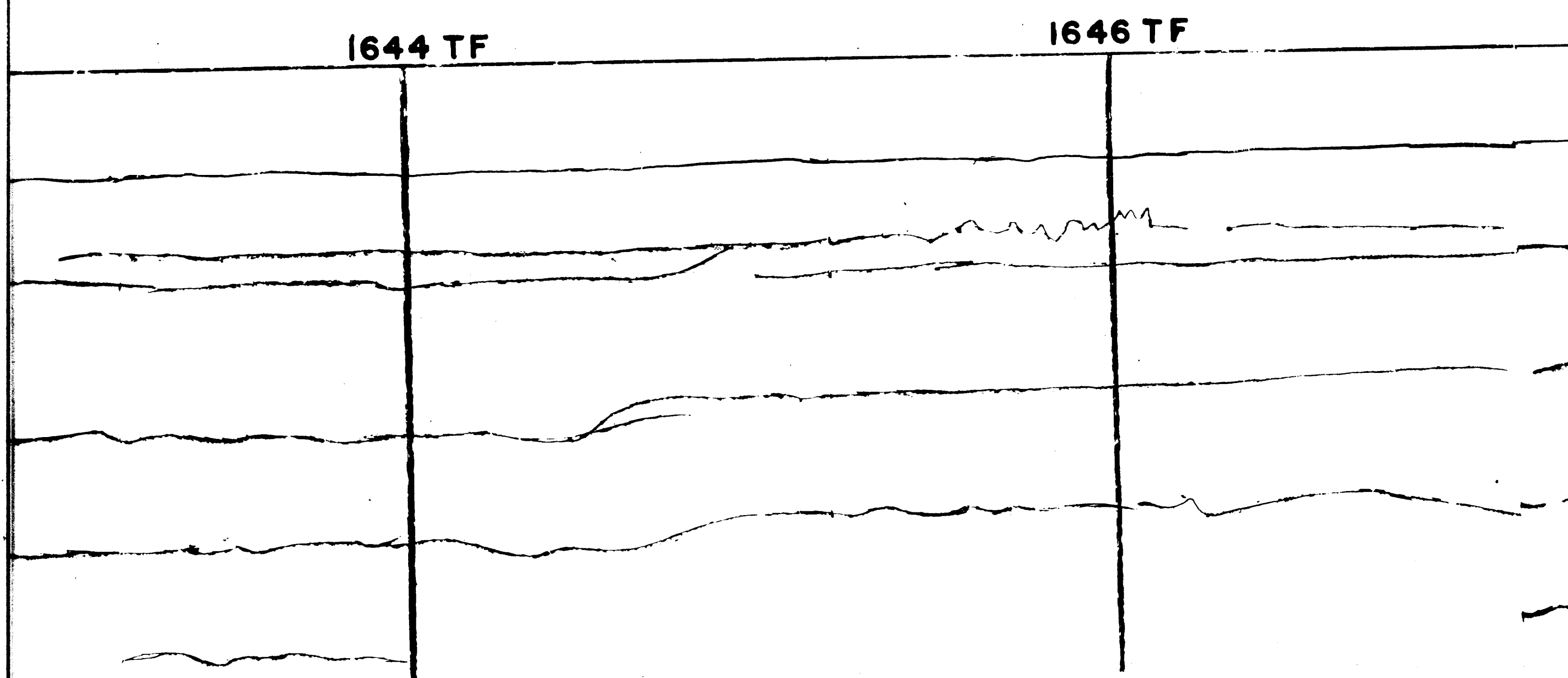
o. 3

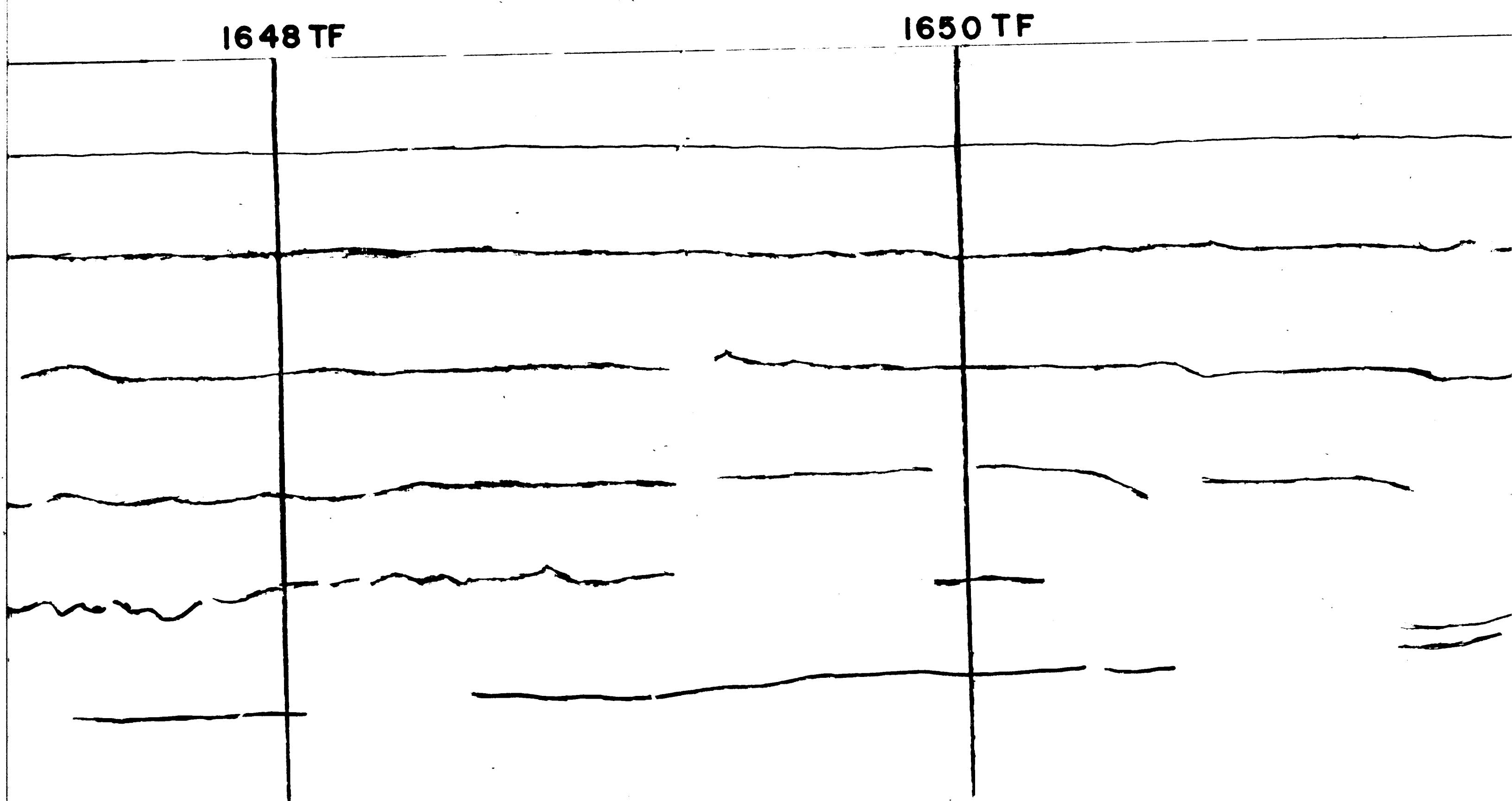
FINE TO COARSE SANDY CLAYEL
9' STIFF CLAY, TRACE OF GRAVEL
5' SOFT CLAY, TRACE OF GRAVEL
FINE SAND
O' SOFT CLAY TRACE OF GRAVEL
' CLAY AND BOULDERS

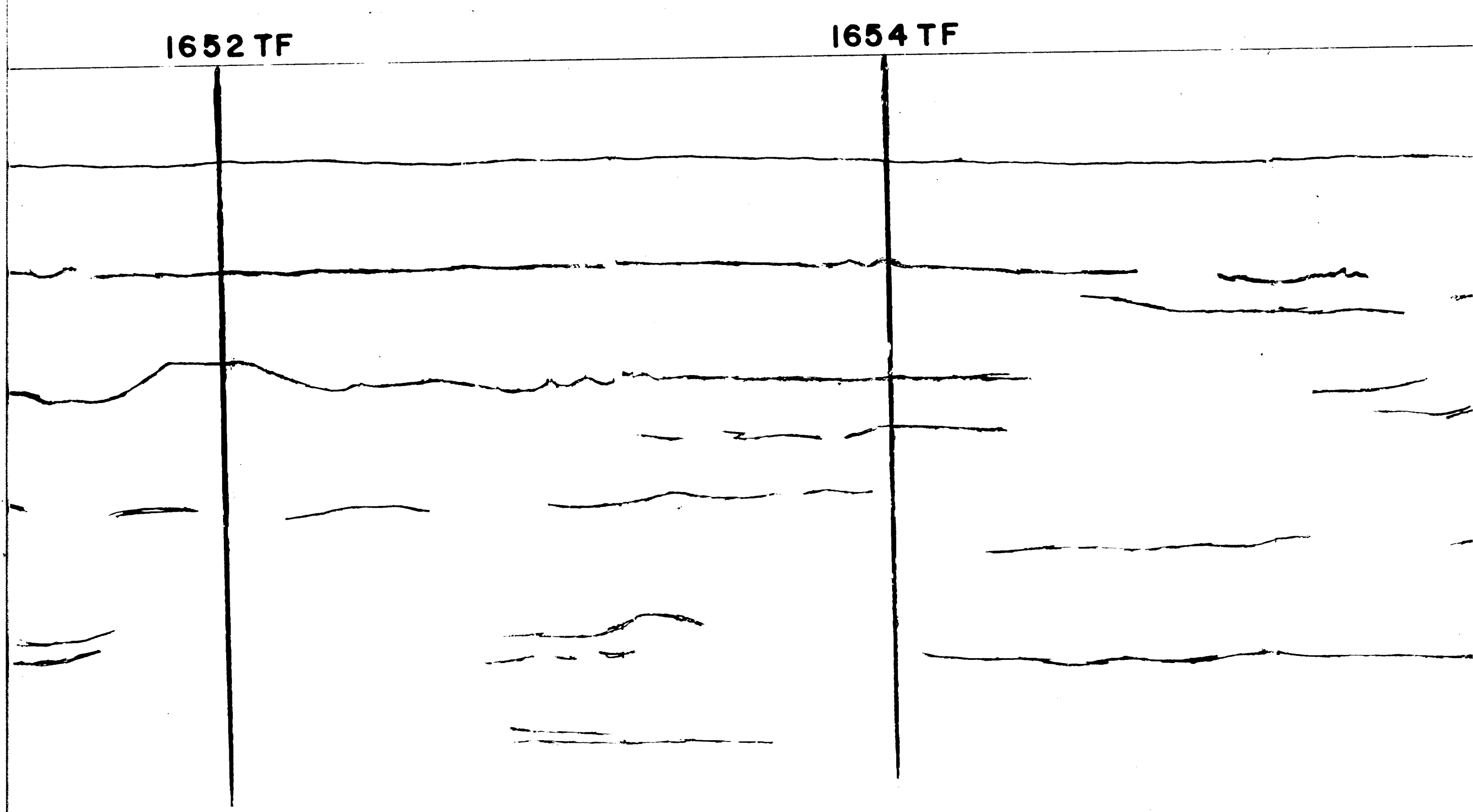
SHALE WITH CLAY SEAM
SHALE

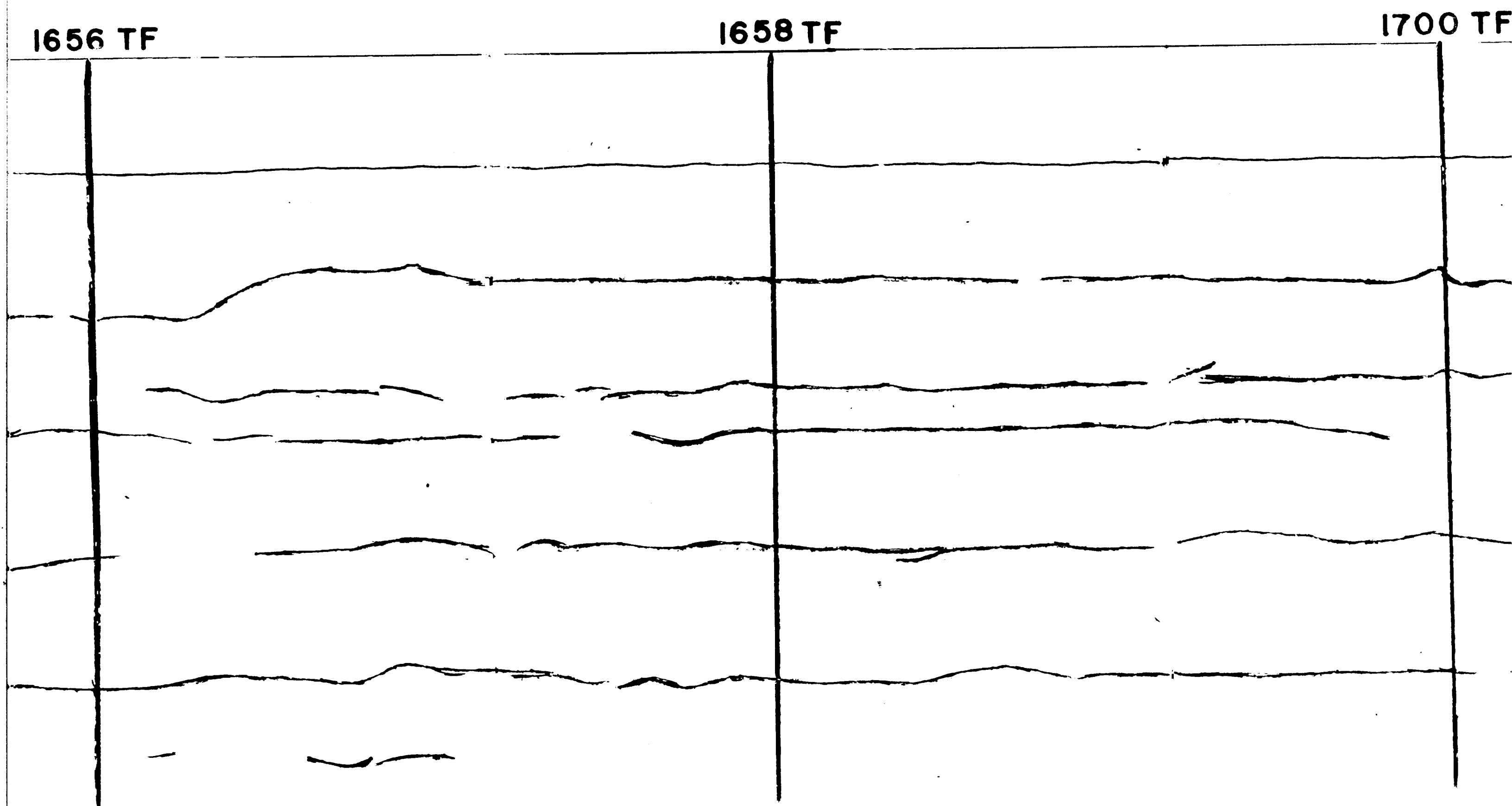



1640 TF
1642 TF


1644 TF
1646 TF

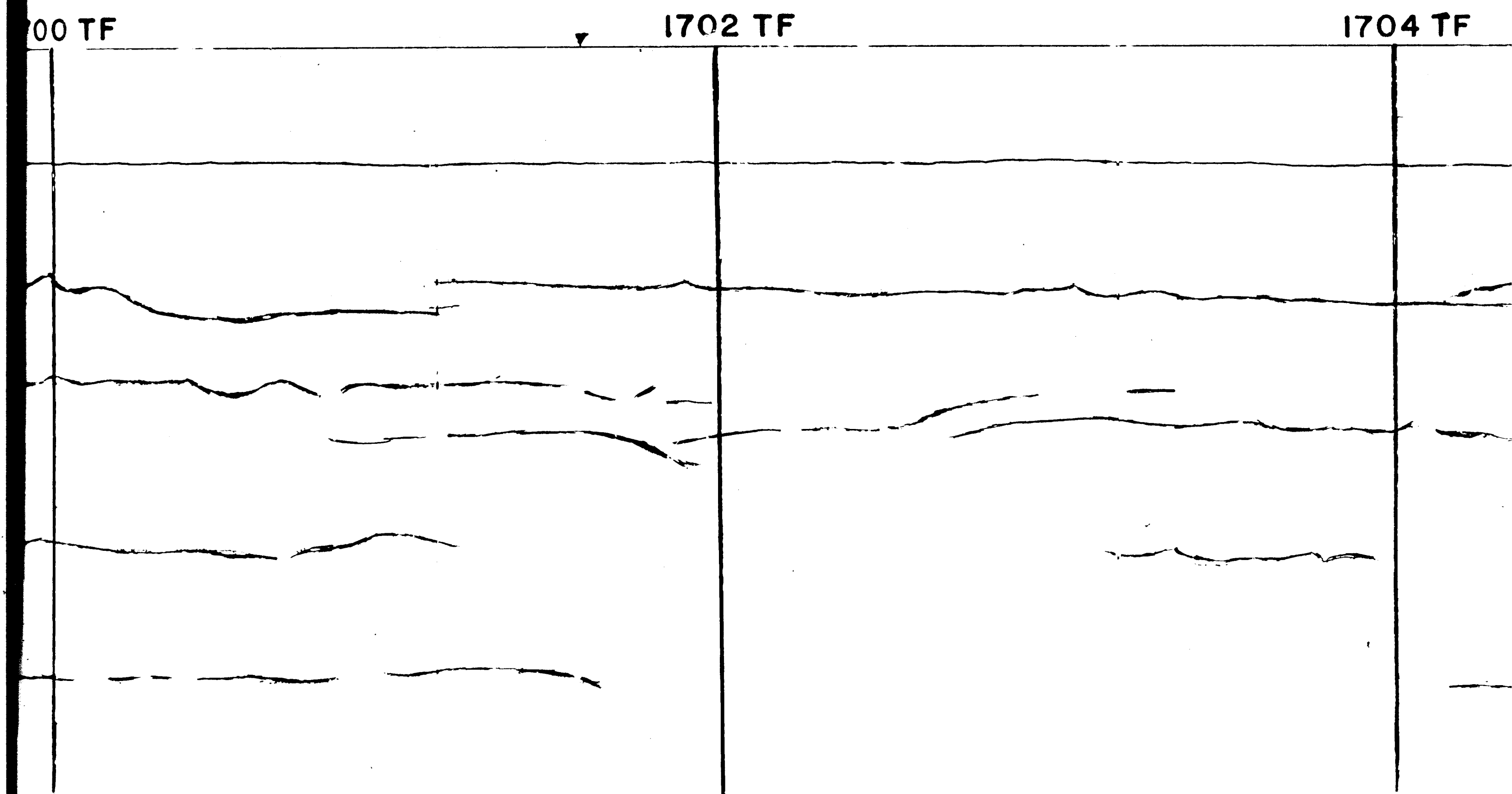

1648 TF
1650 TF

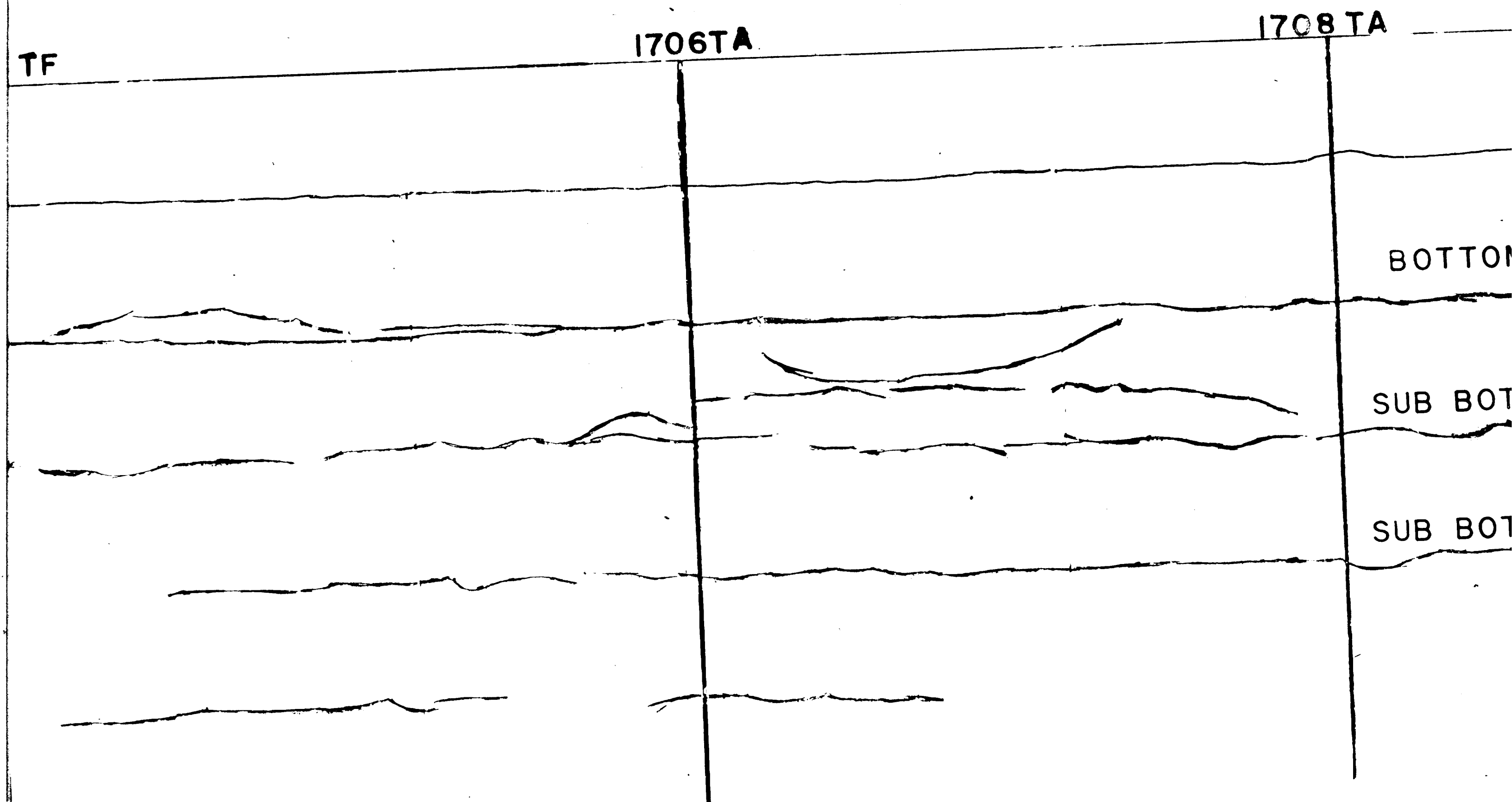

1652 TF
1654 TF

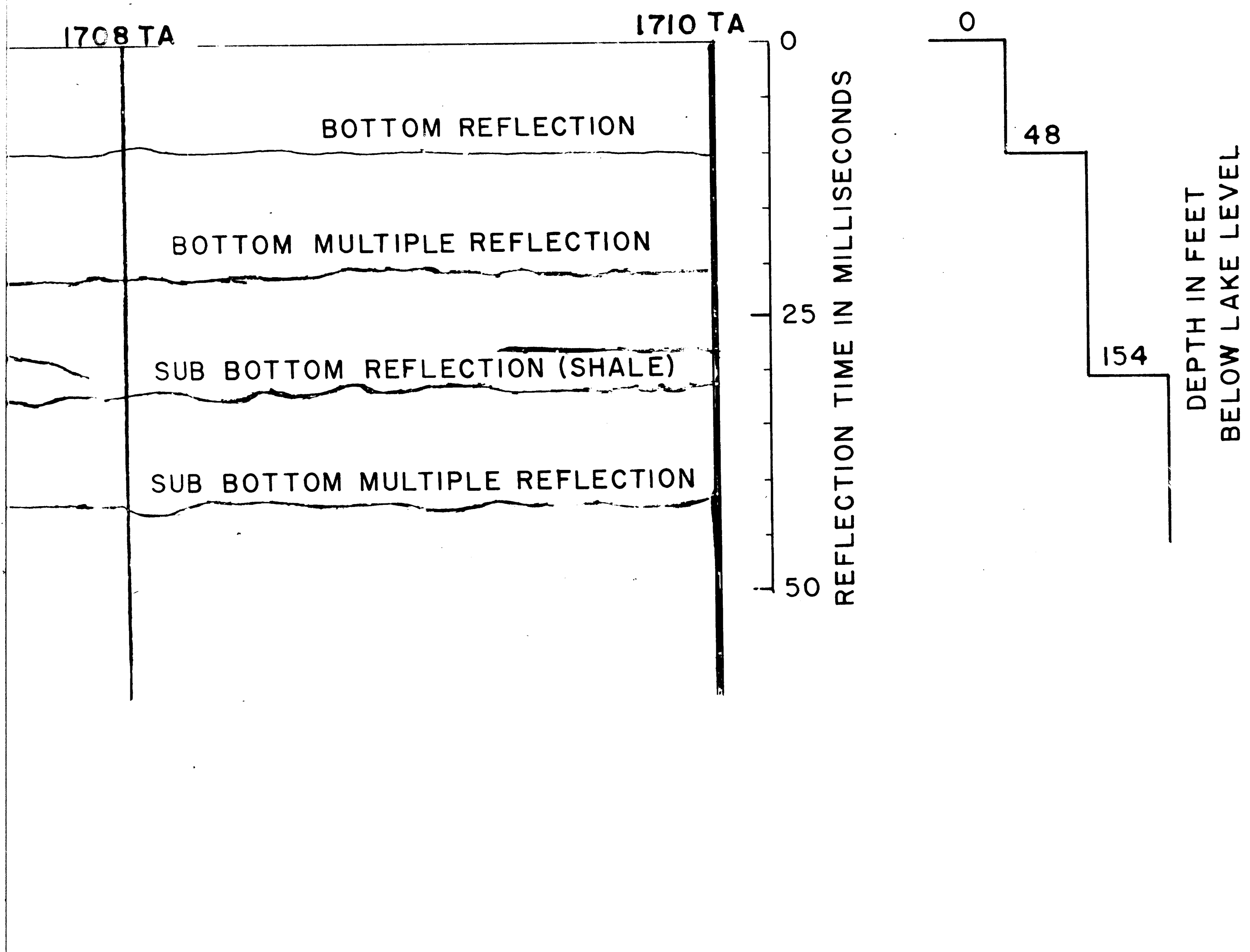

1656 TF
1658 TF
1700 TF

TEST BORING No.4

46' WATER		
103.7' GLACIAL DRIFT	3.6'	SAND AND GRAVEL
	18.0'	FINE SILTY CLAY AND GRAVEL
	4.0'	SAND AND GRAVEL, SOME CLAY
	9.0'	MED. STIFF CLAY
	9.0'	MED. STIFF CLAY, SOME GRAVEL
	60.1'	MED. STIFF TO STIFF CLAY WITH OCCASIONAL TRACE OF GRAVEL
SHALE	2.9'	MED. HARD SHALE




TF
1706TA
1708 TA
BOTTON
SUB BOT
SUB BOT


1708 TA
1710 TA
BOTTOM REFLECTION
BOTTOM MULTIPLE REFLECTION
SUB BOTTOM REFLECTION (SHALE)
SUB BOTTOM MULTIPLE REFLECTION
0
25
50
REFLECTION TIME IN MILLISECONDS
0
48
154
DEPTH IN FEET
BELOW LAKE LEVEL